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NATIVE PLANT LANDSCAPING FOR POLLINATORS ON EASTERN NORTH CAROLINA SOLAR FARMS

by

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Solar panel farms (SPFs) may be a part of a sustainable solution to pollinator decline and the loss of ecosystem services they provide. Some SPFs are seeking to landscape with diverse native seed mixes, which has the potential to benefit pollinators, the solar industry, as well as surrounding ecosystems and communities. Native plants selected for restoration should be diverse and offer ample resources for pollinator biodiversity. Yet, we lack important knowledge of native plant performance on SPFs and pollinator attractiveness for specific regions, including the Coastal Plain of eastern North Carolina.

To better inform native plant selection for SPFs, I investigated the microclimate under a simulated solar panel, evaluated pollinator visitation to native plant species used in landscaping, and asked how 13 plant species might respond under solar panels. I used Apogee® light meters (Apogee Instruments, Logan, UT) to record photosynthetically active radiation (PAR), both in the shade and unshaded (control) plots, for 2-wk periods in both winter and again in summer 2018. I also recorded temperature during these same times using iButton® data loggers (Maxim Integrated, San Jose, CA). I found PAR at ground level was reduced on average by 82.6% in winter and 79.8% in summer, during peak daylight hours. Temperature also varied under the simulated panel, becoming cooler during the afternoon hours and warmer in the evening and morning, in both winter and summer, possibly enhancing winter germination rates and lowering winter frost mortality under PV panels.

I selected 14 shade-tolerant perennial native plants to evaluate for possible use promoting pollinators on SPFs. Selection was based on known pollinator use, maximum height (to minimize contact with panels), and availability. Select native plant species (10 of the original 14) were also evaluated for pollinator attractiveness in shaded pollinator beds. Correspondence analyses (one based on 23 insect genera and one based on morpho-group, e.g. small native bee, large native bee, etc.) suggested that insects were not randomly visiting these plant species. In both correspondence analyses, *Echinacea purpurea* and *Chrysogonum virginianum* were outliers, suggesting a difference in their insect visitation, driven primarily by visits from *Bombus* sp. to *Echinacea* and *Toxomerus* sp. to *Chrysogonum*. The

remaining eight native plant taxa were clustered, suggesting similarity in their insect visitation patterns. According to the visitation index (visits per floral unit V/F), *Stokesia laevis* was the most, followed by *Coreopsis lanceolata*, *Gaillardia pulchella*, *Asclepias tuberosa*, and *Rudbeckia fulgida*. Least attractive by this measure was *Conoclinium coelestinum*. Shannon's Diversity Index (H') based on genera of visiting insects was calculated using visitation rates for each plant species. *Chrysogonum virginianum* had the greatest diversity index among these ten selected natives, followed by *R. hirta*, *G. pulchella*, and *Echinacea purpurea*. Least attractive by this metric was *R. fulgida*. I then ranked the overall attractiveness of each plant species using a simple combination of their rankings based on the combined Shannon's Diversity index and visitation index. The appeal to insect visitors as shown by the combined ranking suggests that the floral resources of *G. pulchella*, *C. virginianum*, *C. lanceolata*, *A. tuberosa*, *R. hirta, S. laevis*, and *E. purpurea* are most useful to pollinators and could provide necessary resources to eastern North Carolina's pollinators. *Rudbeckia fulgida, C. coelestinum*, and *Marshallia obovata* did not rank as highly, however, did attract insects.

I also compared germination performance for 13 of the original 14 native species under simulated shading by solar panels in a greenhouse experiment. *A. tuberosa, C. lanceolata, E. purpurea, C. coelestinum, G. pulchella, M. obovata, R. fulgida, R. hirta,* and *S. laevis* germinated successfully and show promise for landscaping on SPFs. I then conducted a field germination experiment using eight native plant species that showed high germinability in the greenhouse to compare germination rates under and outside simulated solar panel arrays. In the field, *G. pulchella* (Indian blanket), *R. hirta* (black-eyed Susan), *E. purpurea* (eastern purple coneflower), *C. lanceolata* (lanceleaf coreopsis), and *S. laevis* (Stokes' aster) had the highest and most rapid germination and show the most promise for use on SPFs. However, field germination was reduced when compared to greenhouse results for *A. tuberosa, C. coelestinum, C. lanceolata, E. purpurea*, *R. fulgida*, *R. hirta*, and *S. laevis,* suggesting microclimate and weedy competitor effects.

Seed mixes with high proportions of fast establishing natives such as *G. pulchella* and *R. hirta* could be useful in establishing vegetation on SPFs. Additionally, land preparation techniques and sowing a cover crop with these native plant species may increase successful germination and establishment of pollinator habitat on solar farms of eastern North Carolina. More *in-situ* studies of native plant performance are needed to provide more information to landscape managers and reduce pressures on native seed stocks. Use of native plants for landscaping on SPFs remains a promising option for promotion and maintenance of both plant and insect biodiversity on these human-modified landscapes.

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By

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CHAPTER 1: INTRODUCTION TO NATIVE PLANT LANDSCAPING ON SOLAR FARMS IN EASTERN NORTH CAROLINA

1.1 INTRODUCTION

As human population increases, agricultural demand increases (Tilman 1999). In response, more land is being used for farming, thereby degrading or eliminating natural areas relied upon by native plants and wildlife (Olwell & Riibe 2016). This negative impact on ecosystems also has translated to a loss of important ecosystem services to humans. One such impact is decline of pollinators, particularly bees, associated with habitat loss, the use of agrochemicals, invasive species, climate change and other anthropogenic effects (Kearns et al. 1998; Potts et al. 2010; Thomann et al. 2013). Regional declines of honey bees in the U.S. are well documented (Kearns et al. 1998). Declines of other insect pollinators, including native bees, also have been described globally (Williams et al. 2007; Grixti et al. 2009; Potts et al. 2010, Thomann et al. 2013). The implications of pollinator loss could be very costly for agrosystems worldwide (Potts et al. 2010; Vanbergen 2013). These pressures are raising awareness on the need to improve efficiency of our land use.

The energy sector has been called upon to lead in improving sustainable practices. Renewable energy technologies, such as solar power (also referred to as photovoltaic cells, PV), are being embraced on a large scale, having increased 43-fold in the United States in the last decade (Weissman et al. 2017). This increase in solar energy is not without challenges, as these solar panel farms (SPFs) occupy large parcels of land. Given that the supply of land is fixed, improving land use methods will be an integral component of reducing pressure on both agricultural land and native wildlife. One such method to limit negative impact on biodiversity involves the creation of native pollinator habitat, using native plants, for landscaping SPFs. Native plants offer forage and shelter resources and have proven more useful for native pollinators than the traditional gravel and turf grasses used at SPFs (Montag et al. 2016). Established in previous studies, installed pollinator habitat near agriculture has the potential to enhance local pollinator communities (Kennedy et al. 2013). Healthy and diverse pollinator populations can benefit agriculture in the form of increased crop production and stability (Klein et al. 2007; Rogers et al. 2014). In addition to reducing land use impact, native plants are well adapted to local climate conditions and reduce soil erosion and storm water runoff due to complex root systems (Moore-O'Leary et al. 2017). Other benefits include

improved local water quality and soil health (nutrient cycling, microbial diversity) (Moore-O'Leary et al. 2017). Initially, there are increased costs expected as native plant seed mixes tend to be more expensive than non-native grasses; however cost saving of reduced site preparation and maintenance, such as grading, mowing, reduced spraying of herbicides and pesticides is estimated to far outweigh these initial costs (Swanson 2015; Semeraro et al. 2018). Additionally, use of greater plant biomass rather than turf or gravel can reduce ambient temperatures as a result of plant evapotranspiration. These lower temperatures can then increase electrical power yield (Dubey et al. 2013). Pollinator habitat can also increase community support for new solar projects (Wratten et al. 2012) and provide a potential revenue opportunity from honey production, seed cultivation, or animal grazing (Hoffacker et al. 2017; Semeraro et al. 2018).

Establishment of native plants on SPFs is still in its infancy, particularly in the southeastern US. However, there have been established successes using height-restricted seed mixes in the UK (Montag et al. 2016). In the US, two states have incentivized this practice through legislation, giving certification to SPFs who meet pollinator habitat standards. In 2016, the state of Minnesota introduced Bill HF 3533, which outlines guidelines for voluntarily incorporating native habitat for pollinators on SPFs (MN State Legislature 2016). This legislation was followed by the installation of over 930 ha of pollinator habitat (MN Commerce Department 2019). Maryland initiated similar legislation in 2017 (MD General Assembly 2017). There is growing interest in native plant landscaping for pollinators within the solar industry (Moore-O'Leary et al. 2017), and some North Carolina solar companies (including Strata Solar, LLC and Cypress Creek Renewables, LLC) have initiated small-scale pilot studies to evaluate the performance of native seed mixes.

Locally, portions of North Carolina's piedmont and coastal plain support solar energy production of over 5,000 KWH/m^2 per day (NREL 2017). Solar resource potential, financial incentives, and availability of water are driving immense growth in solar capacity (Fernandes et al. 2010). North Carolina is now second in the nation for solar power, capable of producing 5,260 MW per hour (NC Solar 2019). North Carolina is an optimal state to promote pollinators using native plants on SPFs. Several agricultural crops grown in state are benefitted by pollination (soybeans, cotton, peanuts, melons, blueberries, pumpkins, cucumbers, etc.), many within 35 ha of utility solar scale energy zones (Walston et al. 2018).

Native seed mixes can be used to revegetate all or part of a SPF, including buffer areas (Swanson 2015; Semeraro et al. 2018). Within PV panel arrays, use of vegetation no more than 91 cm tall is

suggested to minimize contact with panels (MNDNR 2016). Several companies offer native seed stock for pollinator habitat restoration and provide custom mixes based on region and height (Swanson 2015). Nonetheless, hurdles remain for solar industry leaders as *in situ* studies on NC solar farms are in their infancy. More information on native plant performance in a shaded setting and pollinator usefulness is needed to guide management decisions. Also, use of seed requires successful germination, seedling establishment, plant survival, growth, and ultimately patterns of light and temperature for asexual and/or sexual reproduction for self-sustaining populations. More *in-situ* studies of plant success could offer additional options of useful species and reduce pressure on limited seed stocks (NCCETC 2017).

In response to these challenges, I quantified how solar panels modify plant microclimate through evaluation of differences in photo- and thermoperiod, both under and outside a constructed solar panel in Greenville, NC, on the coastal plain. Using these data and information from the literature on height, shade tolerance, and use by pollinators, I identified 14 native herbaceous perennial species for evaluation of performance and pollinator enhancement on SPFs. Initially, I monitored these selected perennials in landscaped beds to determine usefulness to pollinators. I then evaluated the germination performance of these selected natives in a greenhouse experiment and secondarily, in a field germination experiment using constructed PV panel arrays. My objective was to help evaluate the suitability of 14 perennial plants as well as their attractiveness to pollinators for their use in landscaping on SPFs.

CHAPTER 2: HOW DOES A SIMULATED PV PANEL ARRAY ALTER LIGHT AVAILABILITY AND TEMPERATURE IN EASTERN NORTH CAROLINA?

2.1 INTRODUCTION

Some solar panel farms (SPFs) have incorporated pollinator habitat in the form of diverse native plant seed mixes (Montag et al. 2016). A diverse assemblage of floral resources that bloom from early spring into late fall is recommended by the North Carolina Pollinator Alliance to maximize benefits for a species rich community of pollinators on SPFs (NCPCA 2018). To date, few SPFs in eastern North Carolina have created pollinator habitat (personal communications with Strata Solar, LLC and Cypress Creek Renewables, LLC). More information is needed about which native plants will provide pollinator resources as well as thrive in the microclimate created under solar panels to achieve optimal vegetation diversity and coverage of pollinator habitat.

The complexity and variability of site conditions on SPFs, both among and within sites, challenge our ability to predict how the microclimate under or associated with solar panels will impact vegetation success (Marrou et al. 2013; Armstrong et al. 2014; 2016). Depending on the community (e.g., desert or grassland), warming or cooling may occur beneath panels (Armstrong et al. 2016). PV panel array effects on microclimate have previously been explored in the UK. Armstrong et al. 2016 reported a decrease in mean temperature under PV panels (by 5.2 °C in summer and 1.7 °C in winter) and a reduction of photosynthetically active radiation (PAR) by 92% at a height of 130 cm under PV panel arrays. This sampling height may underestimate the amount of PAR available for vegetation at ground level. The authors also found that soil temperature was cooler under the panels in the summer and warmer in the winter (up to a 5.3 °C difference). Summer air temperatures measured at 50 cm above ground level were as expected: cooler than ambient temperatures under panels during the day and warmer at night from April to September. Interaction of climate variables such as temperature and precipitation also may dictate the plant functional groups and species that can successfully colonize an area (Dorrepaal et al. 2009; Valladares et al. 2016). Shading also alters additional abiotic and biotic conditions (Valladares et al. 2016). Furthermore, SPF microclimates are not readily translatable across regions. Within-site differences in precipitation distribution, soil microbe communities, and nutrient cycling also have been documented for sites in the UK (Armstrong et al. 2016), suggesting that each region will have unique SPF microclimates.

According to the Köppen–Geiger climate classification system, the UK experiences a highland climate with evenly distributed rainfall and summer temperatures of less than 22 °C (Geiger 1954). In contrast, eastern NC has a humid subtropical climate, with peak temperatures around 22 °C and precipitation in the summer months (Geiger 1954). The implications of the microclimate differences caused by solar panels have yet to be evaluated in eastern NC.

2.2 MATERIALS AND METHODS

To better understand the effects of PV panel arrays on microclimate in the coastal plain of NC and better inform plant selection for use on SPFs, I constructed a simulated solar panel array in outer Greenville, Pitt Co., eastern NC (Fig. 1). I compared photosynthetically active radiation (PAR) and temperature under the panel array to nearby control plots for a two-week period in both winter and summer.

I constructed a simulated solar panel array.5 m wide x 4.5 m long; 30 cm above ground surface, oriented at a 31° angle, facing south in an open area, with no shade from nearby trees or buildings. Since solar panel size, orientation, and angle vary among SPF sites (NCCETC 2017), I modeled these details after a nearby solar panel farm in Greenville, NC (Cypress Creek Renewables, LLC, Whichard Rd.). The panel row was constructed using a wood frame and roofing tin as the panel surface. This design was not expected to exactly replicate conditions created by multiple solar panel arrays due to its limited size and substituted materials. Nonetheless, this design can provide useful information on temperature and light conditions.

To document light conditions, I used three Apogee® light meters (Model MQ-200, Apogee Instruments, Logan, UT) to record photosynthetically active radiation (PAR), both in the shade and unshaded (control) plots, for a 2-wk period in both winter 2018 (January 21st-February 2nd) and again in summer 2018 (July 12th-25th). The Apogee® light sensors were affixed with Velcro® to a 60 cm section of 2.5 cm x 10 cm wooden plank to create a level surface for each sensor (Fig. 2). The light meters recorded PAR measurements every 30 sec, taking an average of these measurements every 30 min, and compiling daily totals of each 24-hr period in micromoles per meter squared per day ($\mu mol\ m^{-2}\ d^{-1}$). Shaded and control plot PAR averages were compared during maximum photoperiod (10:00 to 15:00).

During these same 2-wk periods, I also collected air temperature data using Thermochron iButton® data loggers (DS1921H-F5#, Thermochron High Resolution 15/46°C, Maxim Integrated, San Jose, CA)

both in the shade and control plots (N=5). Air temperatures were recorded every 10 min. The iButton® data loggers were protected by hand-built solar radiation shields made to allow airflow and protect the iButtons® from water, modeled after a similar Hobo® datalogger shield (ONSET RS3B Solar Radiation Shield, http://www.onsetcomp.com/products/mounting/rs3-b). One of the iButtons failed to record during the winter sample period, thus only four replicates were used. Mean air temperatures in shaded and control plots were compared to gain insights into microclimates to help select candidate native vegetation for SPFs in eastern NC.

2.3 RESULTS

I found the simulated PV panel array reduced PAR by an average of 82.6% ± 0.07 SE in winter, 2018 (Fig. 3) and 79.8% ±0.06 SE in summer 2018 (Fig. 4) during peak daylight hours (10:00-15:00). Peak reduction of PAR in winter (90-94%) occurred when available PAR exceeded 1000 μmol $m^{-2}s^{-1}$. In the summer, peak reduction (89-95%) occurred when available PAR exceeded 1600 μmol $m^{-2}s^{-1}$.

The results of the temperature measurements showed a pattern of warmer air under the panel during the evening and morning hours, and warmer air in the control plots during the afternoon in both winter and summer (Fig. 5,6). During the evening to morning hours, temperature under the panels was up to 3.85 ˚C warmer under panels in the winter (Fig. 7) and up to 5.53 ˚C warmer in the summer (Fig. 8). In the afternoon hours, air temperature in the control plots was up to 3.81 ˚C warmer in winter and up to 8.2 ˚C warmer in the summer.

2.4 DISCUSSION

Solar panels dramatically reduce photosynthetically active radiation thereby limiting native plant species that can thrive under panels (Armstrong et al. 2016). The results from the simulated panel array confirm PAR was very limited in the shade plots. Under the simulated PV panel array, mean reduction in PAR (82.6% ± 0.07 SE in winter, 2018 and 79.8% ±.06 SE in summer 2018) was lower than previously reported in the UK (92%, Armstrong et al. 2016); the difference is likely due to latitude and climactic differences, as well as the difference in the sensor height, and reduced size of my simulated PV panel array. During the summer period peak daylight hours, I found PAR availability under the simulated panel ranged from 75 to 380 μmol $m^{-2}s^{-1}$, with more light available in the afternoon hours (Fig.4). During this time, PAR in the control plots ranged from 225 to 2150 μmol $m^{-2}s^{-1}$ (Fig.4). A reduction of 80%, as seen

from these results, suggests that plants selected for landscaping under solar panels must be highly shade tolerant. Past plant shade studies have described effects of limited light availability on plant success. In one such study, *Tetrastigma hemsleyanum* (in the grape family, Vitaceae) showed photosynthesis was very limited when PAR was under 200 μmol $m^{-2}s^{-1}$ (Dai & Lu 2009). Others have described the optimal PAR reduction as 40-60% for certain shade tolerant species (Beer et al. 1997). While the PAR I report under the simulated panel was low, shade tolerant plants have strategies to reduce their demand for solar radiation (Boardman 1977). Plants can adapt to shaded environments in several ways: 1) by altering growth strategies, such as orienting leaves toward light, or 2) by conserving resources, such as reduced transpiration rates and production of thinner leaves with lower protein and chlorophyll levels (Boardman 1977; Givinish 1988). Microclimate conditions such as humidity and water availability can dictate a plant's ability to succeed using such strategies (Givinish 1988). Additionally, the design of PV panel arrays on SPFs (size and height above ground surface) may permit a variable amount of PAR to reach vegetation under the panels. Plants close to the array perimeters will likely experience edge effects similar to forest edge communities, where less shade tolerant taxa can establish (Gehlhausen et al. 2000).

Similar to findings on a UK solar farm (Armstrong et al. 2016), the temperature results I report here may present potential benefits for plants that can tolerate the low light conditions under PV panel arrays. In summer afternoons temperature is reduced under the simulated panel array by up to 5.5 °C. A reduction in peak temperatures under PV panel arrays could be favorable to vegetation; intense temperatures have been shown to reduce yield in some crops (Hatfield & Prueger 2015). A benefit of reduced radiation, plant species under the panels are expected to experience less water stress, which could partially counteract effects of limited PAR availability (Givinish 1988, Valladares et al. 2016). Reduced water stress also has the potential to reduce germinant mortality (Valladares et al. 2016). In the winter, increased temperatures under the panels along with the presence of the panels themselves, may reduce low temperature stresses and frost as frost damage is known to increase as overstory decreases (Groot & Carlson 1996). This temperature variation also has the potential to alter microbial community productivity (Armstrong et al. 2014) and the number of GDD (growing degree days) per year (Armstrong et al. 2016) and impact germination. Previous studies have noted that an increase of 4-5 °C resulted in increased germination rates (Song et al. 2005, Mondoni et al. 2012). Warming of 4 °C has also been shown to initiate fall

germination in some plant species (Mondoni et al. 2012), which could be a potential benefit for plants in areas with mild winters.

The microclimates within a SPF also have the potential to impact foraging behaviors of insect visitors. Pollinator behavior is known to be influenced by light environment and temperature (Herrera 1997; Kilkenny & Galloway 2007; Lomeli-Flores et al. 2010). In one study, 59% of pollinators showed a preference for sun or shade (Herrera 1997). Bees in the genera *Bombus* and *Halictus* were found to prefer plants in sun to plants in shade (Kilkenny & Galloway 2007). In contrast, some Hymenopterans and Dipterans have been found to prefer shaded habitats (Herrera 1997; Jha & Vandermeer 2009). Temperatures have also been shown to affect foraging activity in *Bombus* sp., with high temperatures resulting in reduced activity (Kwon & Saeed 2003). Yet, SPFs are reported to support greater insect diversity when seeded with native plant seed mixes compared to adjacent unseeded natural areas; bumble bee and butterfly diversity was increased on SPFs in the UK, compared to nearby control plots with unaltered vegetation (Montag et al. 2016). The diversity of microclimates within a solar farm (full sun vs. shade and corresponding cooler and warmer areas) may contribute to increasing diversity within the pollinator community. The effects of the microclimate differences are nuanced and vary not only within sites, but among sites. Impacts of the PV microclimates on vegetation, microbial communities, and insect visitation on SPFs, are likewise expected to vary, and merit further research.

CHAPTER 3: SUCCESS AND INSECT VISITATION OF NATIVE PLANTS IN LANDSCAPING

3.1 INTRODUCTION

Native plant landscaping is still in its early stages and more information is needed about native plant performance to inform conservation biologists and guide market development (Lubell 2017). Ecotype, provenance, or cultivar information is often lacking, limiting success of native plants in application (Vogel et al. 2005; Kramer et al. 2019). Additionally, native forbs available from nurseries often are not successful in restoration applications or have altered ecosystem function (Lubell 2017; Kramer et al. 2019). Despite these difficulties, past pollinator habitat restoration efforts have succeeded in increasing bee diversity (Williams et al. 2015). Improved connectivity of native areas in the landscape is also beneficial for pollinator recovery (Walston et al. 2018).

Establishing diverse native pollinator habitat on solar farms may be part of a solution to pollinator decline. However, limited information exists about which plants are most beneficial to pollinators, both temporally and geographically (Harmon-Threatt & Chin 2016). Ideally, restoration efforts for pollinators contain a diversity of plants that provide ample nectar and pollen resources throughout the growing season (Menz et al. 2011; Tuell et al. 2014). Previous studies have quantified frequency of insect visitors in a community of plant species to describe relative usefulness to pollinators (Memmott 1999; Gibson et al. 2006; Tuell et al. 2014). Though insect visitation patterns are complex, quantification of visitation rates can lend insight into insect visitation drivers such as nectar and pollen resources (Forup & Memmott 2005).

More information about native plant pollinator attractiveness is needed to discern which native plants can support the greatest abundance and diversity of pollinators for each region (Menz et al. 2011). In particular, more pollinator attractiveness studies are needed to assess eastern North Carolina's native plants for pollinator usefulness. This critical biological knowledge can further inform decision-making for both solar farm landscape managers and conservation biologists in the region. As part of this work I investigated a collection of NC native plants for their usefulness to known pollinating insects and asked whether NC native perennials are attractive to pollinators?

3.2 METHODS AND MATERIALS

3.2.1 PLANT SELECTION METHODS

Fourteen native forb species were selected using a review of the horticultural literature to evaluate performance by these plant species for potential use in solar farm landscaping. I selected these forbs based on their life history (perennial), flowering height (<120 cm at flowering), shade tolerance (Table 1), pollinator resources (nectar, pollen, larval habitat) (Table 2), use in other plant-pollinator efforts (Appendix A), and availability from local nurseries (Appendix B) most recommended by the North Carolina Botanical Garden. Local nurseries were selected as sources for these plants to use individuals hopefully conditioned to the climate of the coastal plain of eastern NC. I also included native plant species that differed in their flowering phenology to provide pollinator resources throughout the growing season (Table 1, Karamaouna et al. 2019).

3.2.2 FEED A BEE™ POLLINATOR BED INSTALLATION METHODS

To evaluate these 14 selected native plant species for pollinator usefulness and performance in a shaded setting, I observed insect visitation to plants established in landscaped beds on the campus of East Carolina University (ECU), in Greenville, NC. In Fall 2017, with support from Bayer CropScience Feed A Bee™ program (www.feedabee.com) and ECU Grounds Services, we established two beds with these selected plants in two shaded habitats (one near the Belk building and one near Lake Laupus at West Campus). ECU Grounds services prepared the beds, tilling to a depth of 15 cm on October 27th. The flower bed at Belk Campus is 30.4 m long and divided into 24-1.2 m x 1.8 m replicated subplots. Planting for this site occurred in fall 2017 and spring 2018. In each subplot, we planted one each of the following native perennial forbs: *Asclepias tuberosa* L. spp. *tuberosa*, *Chrysogonum virginianum* L. var. *virginianum*, *Conoclinium coelestinum* (L.), *Coreopsis lanceolata* (L.) D.C., *Echinacea purpurea* var. *purpurea* L. Moench (Kim's knee-high cultivar), *Gaillardia pulchella* Foug., *Phlox divaricata* L., *Marshallia obovata* (Walter) Beadle & F.E. Boynt. var. *obovata*, *Rudbeckia fulgida* Aiton, *Rudbeckia hirta* L., and *Stokesia laevis* (Hill) Greene, (Table 1, Fig. 9). Taxonomy follows that of USDA Natural Resources Conservation Service (https://plants.sc.egov.usda.gov/java/). The flower bed adjacent to Lake Laupus also was planted in fall 2017 and spring 2018 but was not included in the pollinator observation study due to resource limitations. This bed is approximately half the size of that at Belk Campus and includes the native forbs *Aquilegia canadensis* L., *C. virginianum, C. coelestinum, Geranium maculatum* L., *Sanguinaria canadensis* L., and *E. purpurea* (Fig. 10). At both locations, three native woody shrubs (*Rhododendron catawbiense* Michaux, *Ilex*

glabra (L.) Gray*, Eubotrys racemosa* (L.) Gray), a native sedge (*Rhyncospora colorata* (L.) H. Pfieffer), and a native grass (*Chasmanthium latifolium* (Michx.) Yates) also were replicated across each of the subplots at each bed for landscape aesthetics (Fig. 9, 10).

3.2.3 POLLINATOR OBSERVATION METHODS

Beginning in May 2018, I monitored ten of the 14 selected forbs for insect visitor abundance and diversity using an observational study at the Belk Feed A Bee™ site. Four forbs were not monitored: *A. canadensis*, *G. maculatum*, *P. divaricata* flowered prior to May 2018, and *S. canadensis* did not flower in 2018. On 20 occasions from May to September 2018, I observed each of the 24- 1.2 m x 1.8 m subplots once for 10 mins, randomly selected for sequence of observation, except when there were no flowers present. This time frame was chosen for peak anticipated insect activity. During these observations, time of day, number of floral units present, phenology of each plant (flowering period), and insect visitors were recorded and photographed, when possible (Fukase & Simons 2016). Floral units present can provide quantification of pollinator resource availability when pollen and nectar amounts are not directly measured (Szigeti et al. 2016). For native plants in the family *Asteraceae* (*Chrysogonum virginianum*, *Conoclinium coelestinum*, *Coreopsis lanceolata, Echinacea purpurea, Gaillardia pulchella, Marshallia obovata, Rudbeckia hirta, Rudbeckia fulgida, Stokesia laevis*), each composite inflorescence was defined as one floral unit. For the compound umbels of *Asclepias tuberosa,* each individual flower was counted as one floral unit. Observations were made from 60 cm in front of the plots on fair weather days between the hours of 900-1600 (Rogers et al. 2014). Insect visits were defined when insects landed on the floral parts of the plant. Individual visitors were not tracked. Each time the insect took flight and re-landed, it was counted as a distinct visit (Boff et al. 2018). When possible, insect visitors were identified to genus in the field (Rogers et al. 2014). Unknown specimens were collected for further identification in the laboratory when necessary. Insects were secondarily identified by collaborative entomologists when possible with photos and specimens (www.bugguide.net, Elsa Youngsteadt and Hannah Levenson, NC State University).

3.2.4 STATISTICAL ANALYSIS

I compared insect attractiveness among the native plant species using a visitation index of average number of visits per floral unit (V/F). I also used Shannon's Diversity Index (H'), using the following formula:

$$H' = -\sum_{i=1}^{s} p_i \ln p_i$$

where p_i is the proportion of visits by each insect visitor out of total visits to each plant species. Shannon's index was calculated from visitation rates by insect genus (or tribe in the case of *Augochlorini*) for each plant species (Grover et al. 2017) to rank these plant species for attractiveness. This index takes both diversity of insects and evenness of visitation rates into account. I then ranked overall attractiveness of these native plant species by a simple addition of their rankings within the Shannon Diversity Index (H'), and visitation index, to give a more comprehensive rank that included both diversity and frequency of insect visitors.

To confirm distinct relationships between the ten native plant species and their insect visitors and provide insights about visitation patterns related to insect or native plant type, I performed two correspondence analyses using SPSS (Version 24, Cary, NC). Correspondence analyses can be used for large data tables to define relationships between categorical variables in a multidimensional space (Ivy 2001). The categorical variables in this case are insect visitors and plant species. Other studies have previously described plant-pollinator networks using correspondence analyses (Potts et al. 2003; Morales & Aizen 2006). It is expected that insects and plants that are close together within the dimensional space are related in some way to each other. The first correspondence analysis compared the native plant species with their insect visitors organized by genera (or tribe in the case of *Augochlorini*). My second correspondence analyzed insects organized into morpho-groups (e.g., small native bee, large native bee, etc.). This distinction can provide more information about what plant or pollinator traits may be guiding visitation choices, as different pollinator groups, or guilds, may share common characteristics, such as mouthpart length (Newman et al. 2014).

3.3 RESULTS

3.3.1 INSECT VISITATION AND DIVERSITY

I recorded a total of 1,935 insect visits during the 21 weeks of 10 min observations of plots with ten native plant species at the Belk Feed a Bee™ site. Individual subplots were collectively observed 468 times, a total observation time of 4,680 min. During the observational study, all ten native plant taxa were visited by insects known to function in pollination of plant taxa, determined from a survey of the literature. In

total, 23 genera were identified visiting, including ten bee genera, five wasp genera, four genera of butterflies (Lepidoptera) and four genera of flies (Diptera) (Table 3). Due to the infrequency of sightings (<5), visits by beetles (Coleoptera) were not recorded. Caterpillars were observed on *A. tuberosa* and *R. hirta*, however were not included in the analyses due to no documented roles in pollination. I also observed flowering shrubs *Rhododendron catawbiense*, *Ilex glabra*, and *Leucothoe racemosa* as they were visited by pollinating insects. *Rhynchospora colorata* additionally was visited by pollinating insects from five genera during observations (*Bombus*, *Augochlorella*, *Palpada*, *Physocephala*, and *Sceliphron*).

Halictus spp., native sweat bees, were the most abundant, visiting all ten plant species and representing 72.7% of the visits (Table 3). *Rudbeckia fulgida* received the highest proportion of visits from *Halictus* spp., 430 of the 1407 observed visits (Table 3). *Bombus* spp. were the second most abundant visitors, representing 8.7% of the visits (Table 3). *Echinacea purpurea* received the highest proportion of visits from *Bombus* spp., 110 of the 167 observed visits (Table 3). *Gaillardia pulchella* was also visited by *Bombus* spp. 35 times (Table 3). Syrphid flies from the genera *Toxomerus* were the third most frequent visitor, representing 4.1% of the visits (Table 3). *Chrysogonum virginianum* received the highest proportion of visits from *Toxomerus* spp., 69 of the 81 observed visits (Table 3). *Megachile* sp., native leaf cutter bees, were the fourth most abundant visitors, representing 3.5% of the visits (Table 3). *Asclepias tuberosa* received all 68 of these visits during a single observation day. Small native bees from the genera *Lasioglossum* were the fifth most abundant visitors, representing 3% of the observed visits (Table 3). *Chrysogonum virginianum* received the highest proportion of visits from *Lasioglossum* spp., 45 of the 58 observed visits (Table 3). Small sweat bees of the tribe *Augochlorini* were the sixth most abundant visitors, representing 2.5% of the visits (Table 3). *Chrysogonum virginianum* received the highest proportion of visits from *Augochlorini* as well, 35 of the 48 observed visits (Table 3). Of these frequently observed visitors, native bees *Augochlorini*, *Bombus* spp., *Halictus* spp. and *Lasioglossum* spp. were present for the duration of the growing season (Table 4). The remaining 17 genera were observed visiting less than 20 times.

Based on the visitation index (total observed insect visits per total observed floral units), *S. laevis* was the most attractive, followed by *C. lanceolata*, *G. pulchella*, *A. tuberosa*, and *R. fulgida* (Table 5). The blue mistflower, *Conoclinium coelestinum,* was least attractive by this measure.

3.3.2 SHANNON'S DIVERSITY INDEX

Shannon's Diversity Index (H') was calculated for each plant species using visitation rates of each of the 23 insect genera observed (Table 5). *Chrysogonum virginianum* had the largest diversity index among these ten selected natives, followed by *R. hirta*, *G. pulchella*, and *E. purpurea*. Orange coneflower, *R. fulgida*, was least attractive by this metric. Based on the ranking from the combination of Shannon's Diversity and visitation index ranks, *G. pulchella* was the most attractive plant species, followed by *C. virginianum*, *A. tuberosa*, *C. lanceolata,* and *S. laevis*. The least attractive with this comprehensive ranking was *C. coelestinum*.

3.3.3 CORRESPONDENCE ANALYSIS BETWEEN NATIVE PLANTS AND POLLINATORS

The first correspondence analysis compared the native plant species with their insect visitors organized by genera (or tribe in the case of *Augochlorini*). In this correspondence analysis, the first and second dimensions explain 63.9% (dimension 1 explained 44.6%) of variance in data set. The chi-square of this association was highly significant (2468.475, $p<0.001$, df=198), suggesting that insects were not randomly visiting these plant species. In this correspondence analysis, *E. purpurea* and *C. virginianum* contributed the most to the inertia in dimensions one and two respectively (Fig. 11). Inertia is a measure of the extent to which points spread around the centroid, the average of the categorical variable. In this analysis, the centroid is located around X,Y coordinates (0,0); points furthest from this centroid are contributing significantly to the inertia. Biologically, deviation from the centroid suggests that some characteristic (e.g., morphology, phenology) of the categorical variable (native plant or pollinator) sets it apart from the data-set average. The pollinators that contributed the most inertia were *Bombus* sp. and *Toxomerus* sp.

In the second correspondence analysis, insect visitors were arranged into ten morpho-groups to gain further insights into visitation patterns based on insect morphological differences (Fig. 12). In this analysis, the first and second dimensions explain 80.7% (dimension 1 explained 65.7%) of variance in the data set. Again, *E. purpurea* and *C. virginianum* contributed the most inertia to dimensions one and two, respectively. The morpho-groups that contributed the most inertia were large native bees (LB) and syrphid flies (SF). In both correspondence analyses, the remaining eight native plant taxa were clustered together within these two dimensions, suggesting a commonality in insect foraging patterns. This commonality could

be due to similar flower morphology as seven of these eight are in the family Asteraceae. Forbs in this family have radially symmetrical flowers and easy access to resources. Asters, along with *Asclepias*, are known to largely attract generalist species (Ollerton et al. 2007).

3.4 DISCUSSION

Collectively, the ten native plant species established in ECU's Belk Feed a Bee™ landscaped bed were attractive to 23 genera of known pollinating insects between May and September in 2018. A similar study of bees in urban areas of North Carolina found a range of 22-52 bee species across 18 urban (15 residential and natural) sites with both native and non-native vegetation, using both pan traps and sweep netting (Hamblin et al. 2018). Another study in eastern North Carolina also used sweep netting and pan traps in collection of bees in highbush blueberry farms (Rogers et al. 2014). In this study, over the course of two years 12 genera of bees were identified. In my study, at least 17 bee species from ten genera were observed. My sampling plots were much smaller sample areas than the two previously mentioned studies. That, along with my specific sampling method in only one season, likely limited a full accounting of the entire landscaped area insect diversity. An insect study with similar 10-min plot observation periods within urban garden areas in Ontario recorded 1699 floral visitors in one season from similar nine pollinator guilds (bumble bee, honeybee, small bee, large bee, small fly, large fly, butterfly, wasp, and other) (Fukase & Simons 2016). My observational study attracted a total of 1,935 floral visitors during a similar time-period from a similar number of pollinator guilds. These studies, while not directly comparable, offer some context to the similar insect abundance and diversity observed at the Belk planting site. We expect a trend toward increased species richness at the Belk site, as previous studies have linked increased rates of persistence and colonization at restoration sites through time, with greater age of native plantings (M'Gonigle et al. 2015).

These plant species were ranked, to compare relative attractiveness, using a visitation index of visits per floral unit. Floral densities and pollinator attractiveness relate in a non-linear fashion, with positive effects on pollination at lower floral densities and negative effects at higher floral densities as a result of competition for pollinators (Essenberg 2012). Thus, my visitation index of visits per floral unit (V/F) is an imperfect metric because floral densities and pollinator attractiveness are not directly nor linearly related. Nonetheless, visits per floral unit provides a baseline for comparison of pollinator attractiveness among

these native plants. The visitation index indicated that *S. laevis*, *C. lanceolata*, and *G. pulchella* were the most attractive to insects visitors. Diversity of insects attracted is not taken into consideration using the visitation index, so more information is provided by ranking these species using Shannon's Diversity Index. Shannon's Diversity Index using genera rather than species likely underestimates diversity, however it still provides some additional insights into relative diverse appeal among these selected native plants. When ranked using this index, *C. virginianum*, *R. hirta*, and *G. pulchella* were the most attractive, respectively. Each index describes only one aspect of attractiveness. To provide a more complete picture, I ranked the ten species using a combination of these two indices. When ranks were combined, *G. pulchella, C. virginianum*, *C. lanceolata*, and *A. tuberosa* were most attractive to a diverse community of pollinating insects. *While S. laevis* attracted the greatest proportion of insect visits to floral units, diversity was low compared to the other plant species, reducing its rank with this metric. Because *S. laevis* only presented eight inflorescences during observation, it was less likely than other plant species to be observed being visited by rarer insect taxa. Other studies also have noted the attractiveness of *A. tuberosa*, *C. lanceolata* and *G. pulchella,* and *R. hirta* to pollinators (Fishbein & Venable 1996; Grundel et al. 2000; Buckley 2011; Robson 2014; Tuell et al. 2014). No known studies exist on the pollinator attractiveness of *C. virginianum* or *S. laevis,* but both are described as attractive to pollinators among horticulturists (The University of Texas at Austin Lady Bird Johnson Wildflower Center 2015).

In addition, correspondence analysis confirmed that collectively these ten native plants were highly correlated with both insect taxa and morpho-groups. As indicated by the inertia contributed to dimensions one and two, *E. purpurea* and *C. virginianum* may encourage further insect diversity, particularly bumble bees and syrphid flies, when included in plantings for native pollinators (Fig. 11, 12). *Bombus* sp. are known to forage plants with high nectar and pollen rewards (Vaudo et al. 2016), and specifically have been recorded visiting *E. purpurea* for nectar resources (Vaudo et al. 2014). Plants with longer corollas paired with dark blue or purple inflorescences are known to attract bumble bees (Dlusskii et al. 2004). There is some evidence that syrphid flies, often with short mouthparts, prefer yellow or white flowers with shallow corollas, like *C. virginianum*, that allow access to both pollen and nectar (Colley & Luna 2000; Dlusskii et al. 2004). *Chrysogonum virginianum* also produced the most blooms per plant (Table 5) and had the longest

bloom period of the ten observed plant species (Fig. 13). Resource and morphology differences distinguished these two plant species from the other eight, offering additional resource diversity.

In addition to attractiveness, it is important to reflect on the abundance of resources provided by these ten native plant species. The number of inflorescences observed by these plant species varied widely (Table 5). Top floral producers during my 2018 observations were *C. virginianum*, *R. fulgida*, *C. coelestinum*, and *A. tuberosa*, and *E. purpurea* (Table 5). The fewest flowers were produced by *S. laevis*. These native plants were in a landscaped bed with moderate amounts of shade, providing some insight into floral production that may be seen on SPFs.

The insect genus that visited this collection of native plants most was *Halictus*, native sweat bees. It is worthwhile to note that species in this genus are useful as pollinators of agricultural crops (Kremen et al. 2002). While not all these native plants ranked highly by these indices, all plant species did attract known pollinators. The low growing sedge, *Rhynchospora colorata,* was observed flowering from May through September. It was attractive to five insect genera during observations, suggesting it also provides beneficial resources for our native pollinating insects. Additionally, the native shrubs *Rhododendron catawbiense*, *Ilex glabra*, and *Leucothoe racemosa* were attractive to pollinating insects, and could be useful in SPF perimeter plantings to provide additional floral and habitat resources. Ultimately, this work may provide more information to land managers seeking to include a diversity of plant species in plantings. Both diversity of plants, abundance, and consistency of floral displays for pollinators continuously throughout the growing season are needed to support diverse insect visitors.

CHAPTER 4: WILL THESE SELECTED NATIVE PLANTS GERMINATE UNDER SOLAR PANELS?

4.1 INTRODUCTION

Solar panel farm (SPFs) are comprised of both full sun and highly shaded areas. The availability of photosynthetically active radiation (PAR) and design of the panels also impact the temperature regime within a SPF. Under the photovoltaic panels (PVs), PAR is reduced by 80-92% (See Chapter 2) (Armstrong et al. 2016). These SPF conditions have the potential to impact the plant species or functional groups that can successfully establish and succeed on these microsites (Dorrepaal et al. 2009; Valladares et al. 2016). Native plant seeds selected for establishing ground cover on a SPF need to thrive in both sets of conditions.

Past restoration efforts have noted challenges to native plant establishment including weedy competition (Schramm 1990) and winter mortality (Haan et al. 2012). Efforts to establish vegetation on solar farms have noted the additional challenge of limited light availability under PV panel arrays (Aldina et al. 2017; Beatty et al. 2016). Further complicating the problem, the shade tolerance spectrum used to classify species for horticulture is general and often unclear, with terms such as ‘part sun’ to ‘part shade’ as guidelines (Mellichamp 2014). Another challenge to the use of native plants is construction permitting in North Carolina which mandates that vegetation must be established in less than 90 days after solar installation is complete for sediment control (NCDEQ 1988); as a result, faster germinating winter annuals like rye or fescue are used (Montag et al. 2016). Prairie restoration has been previously described to follow successional stages (Schramm 1990). The first of these stages is dominated by fast growing forbs, followed by an intense competitive establishment stage. Successful seed mixes then need to contain fast establishing forbs, grasses, as well as perennials that can outcompete aggressive weeds (Schramm 1990).

More information is needed to create diverse seed mixes that will successfully germinate and establish under PV panels. To provide more information for landscape managers, I sought to investigate the germination success of 13 NC native plant species in both full sun and 90% shade in a greenhouse experiment and in a field setting, using simulated PV panels.

4.2 METHODS AND MATERIALS

4.2.1 GREENHOUSE GERMINATION EXPERIMENT

Seeds of 13 NC native plants were sown in shaded (treatment) vs. unshaded (control) pots (N=5 pots each) in a greenhouse experiment in spring 2018 to determine germinability of these natives in

reduced light conditions, resembling the microclimate under solar panels. Only 13 of the 14-aforementioned species were used (*Sanguinaria canadensis* L. has double dormancy and was not used in the germination study). Seeds were obtained from American Meadows® (Shelburne, VT), Prairiemoon Nursery® (Winona, MN), and NC Botanical Gardens (Chapel Hill, NC) in January and February 2018 (Table 6). Recent germination test results and seed provenance were also requested when available, as were seed storage conditions, all of which might affect germinability (El-Keblawy & Al-Ansari 2000; Norcini & Aldrich 2007). American Meadows stored the seeds in 18 °C prior to shipping. Prairiemoon Nursery stored the seeds 10-15 °C prior to shipping. The NC Botanical Garden stored the seeds in 19 °C with 35% humidity prior to shipping. Once acquired, seeds were kept in 15-18 °C until March 5, 2018 when seeds were cold-moist stratified.

For each of the 13 species, 500 seeds were cold-moist stratified to promote germination. To stratify, seeds were randomly selected and placed (50 each) in Petri dishes that already contained filter paper topped with autoclaved pool sand, one dish per pot. Care was taken to use only seeds that appeared filled and not atypically small, suggesting infertility. The petri dishes were moistened with deionized water and sealed with PARAFILM™. A total of 130 petri dishes (10 per species) were cold-moist stratified in 1 °C March 5-April 26, for 50 days. After stratification, there were heavy amounts of mold on the stratified seeds of *P. divaricata,* and small amounts on *C. virginianum, G. maculatum, E. purpurea, and A. tuberosa* as well. Observed mold was removed manually from the surfaces of seeds and sand. For germination tests, the seeds were then transferred with the filter paper and sand onto Fafard® 3B/Metro Mix® 830 soilless mix (SunGro® Horticulture, Agawam, MA) in 10.2 cm diameter plastic pots. For each species, five pots had 90% reduced light conditions, representing the conditions created by solar panels (shaded treatment), and five were unshaded (control). White polyethylene shade cloth (SHANS Third Generation Products®, up to 90% UV block) was used to match the light reduction measured in the field (Kellogg et al. 2003). The shade cloth was attached to the top of each shaded pot with a rubber band. All 130 pots were placed in randomly assigned positions within 11 trays of 12 pots each. These trays were filled with tap water to sub-irrigate and keep the pots at field capacity for the duration of the experiment (Kebreab & Murdoch 1999). The water in the trays was changed when algae was present. These 11 trays were placed on the west side of the glass greenhouse, exposed to direct sunlight. Every day the trays were rotated, moving the last tray

to the front. The greenhouse was regulated with fans and vents to keep temperatures between 21-40 ˚C during the germination study.

I recorded the number of germinants daily for 1 mo (Kellogg et al. 2003). A germinant was identified once the radicle or a cotyledon emerged and became visible. Germination percentages were calculated as proportion emerged/number planted in each pot (Van der Walt 2017).

4.2.2 FIELD GERMINATION EXPERIMENT

In Fall 2018 I constructed six simulated PV panel arrays in outer Greenville, NC with a wooden frame (1.2 m wide x 2.4 m long; 30 cm above ground surface) and plywood as the panel surface (Fig. 15). The direction, distance from the ground, and orientation of these constructed arrays were consistent with our model solar farm, however, somewhat reduced due to monetary and other resource limitations. Seeds of eight of the selected native plants (*A. tuberosa, C. coelestinum, C. lanceolata, E. purpurea, G. pulchella, R. fulgida, R. hirta, S. laevis*) were sown in random arrangement inside 28 cm diameter plastic landscaping rings (one species per ring) placed both under each of the six the constructed panel arrays (shaded treatment) and in front of each panel array (control), for six replicates of each species, one species per ring. *Aquilegia canadensis*, *C. virginianum*, *G. maculatum*, and *P. divaricata* were not included due to poor greenhouse germination results. *M. obovata* was not used due to limited seed availability. For seven species, 12 aliquots of 100 seeds each were mixed with 60 cm^3 of fine pool sand for ease of spreading in the ring (six replicates each shade and control). The final species, *Stokesia laevis* has limited seed available; only 50 seeds were used in each of the replicated plots. Seeds were sown by hand on November 5, 2018. After multiple high rain events, it became evident that one replicate was impacted by the prolonged saturation and a trench was added along the edge of that replicate.

Number of germinants and mortality were recorded from December 2018 through April 2019 on a weekly basis. Mortality was calculated as the proportion of total germinants that died in each treatment. Mean germination and survival were compared between shaded and control plots to assess suitability for use on solar farms.

4.2.3 STATISTICAL ANALYSIS

For the greenhouse germination experiment, Student t-tests were performed using number of germinants in SAS (Version 24, Cary, NC) for each species to test the null hypothesis that germination

rates were the same among treatments. Data were confirmed to meet assumptions of normality and the appropriate t-statistics and degrees of freedom are reported for equal or unequal variances. Student t-tests were not used to compare means for field germination or mortality, given so few seedlings had germinated by April 2019.

4.3 RESULTS

4.3.1 GREENHOUSE GERMINATION UNDER 90% SHADE

In the greenhouse germination experiment, seven species had mean germination rates in excess of 50% in the shaded treatment (Fig. 14). These seven species included *Asclepias tuberosa* (mean ± standard error) (85.6% ± 1.24), *Conoclinium coelestinum* (50.8% ± 2.71), *Echinacea purpurea* (90.0% ± 0.89), *Marshallia obovata* (80.0% ± 0.71), *Rudbeckia fulgida* (86.4% ± 1.39), *Rudbeckia hirta* (69.6% ± 1.93), and *Stokesia laevis* (88.0% ± 1.92) (Fig.13). Two species had less successful mean germination rates in the shaded treatment, *Coreopsis lanceolata* (32.4% ± 2.22) and *Gaillardia pulchella* (22.8% + 0.68). There was visible yellowing of germinants in all *Gaillardia pulchella* replicates of both treatment and control pots. Four species had mean germination rates of less than 10% in the shaded treatment; *Aquilegia canadensis* (6.0% ± 0.84), *Chrysogonum virginianum* (2.4% ± 0.58), *Geranium maculatum* (2.8% ±1.15). *Phlox divaricata* did not germinate at all (0%). Mold was present in all the *Phlox divaricata* replicates of both treatment and control pots.

Student t-test results did not show any significant difference ($p>0.05$) in mean germination rates between the 90% shade treatment and control pots in the greenhouse for the 11 native plant species tested. A possible exception may be *E. purpurea*, very near the threshold for significance; however, the difference in mean germinants between shade and control was very small (45.0 ± 0.89 vs. 47.2 ± 0.52, shaded vs. control, respectively, $p=0.053$, Table 7). *Chrysogonum virginianum* and *Phlox divaricata* treatment means were not statistically compared due to low germination.

4.3.2 FIELD GERMINATION UNDER SIMULATED PV PANEL ARRAYS

Germinability in the field was too low to reliably compare mean germination of control and shaded plant species (Table 7). Of the eight native plant species tested in the field germination experiment, most showed a trend of no or reduced germination in the shade, except *Rudbeckia hirta* (21.2% ± 6.50 vs. 12.5 ± 4.11, shade vs. control, respectively). Indian blanket, *Gaillardia pulchella* (42.8% ± 2.87) had the highest

mean germination rate under panels, followed by *Rudbeckia hirta* (21.2% ± 6.50)*, Echinacea purpurea* (13.5% ± 1.52), *Coreopsis lanceolata* (12.3% ± 4.60), and *Stokesia laevis* (9.8% ± 2.63) (Table 7, Fig. 16). In the unshaded control plots, *G. pulchella* (39.0% ± 4.44) again had the highest mean germination rate, followed by *E. purpurea* (13.7% ± 3.28), *Rudbeckia fulgida* (12.8% ± 2.88)*, R. hirta* (12.5% ± 4.11*),* and *S. laevis* (10.7% + 5.87, Table 7, Fig. 16). Blue mistflower, *Conoclinium coelestinum* (2.5 ± 1.18 vs. 3.3 ± 1.63) and orange coneflower, *R. fulgida* (2.2% ± 0.79 under panels) (Table 7, Fig. 16).

Asclepias tuberosa, *Coreopsis lanceolata*, *Echinacea purpurea, Gaillardia pulchella, Rudbeckia hirta*, and *Stokesia laevis* began germinating in December in the field. Mean mortality in the shaded plots was lowest for black-eyed Susan, *R. hirta* (30.5% ± 12.10) and Indian blanket, *G. pulchella* (43.7% ± 3.86) (Fig. 17). Lanceleaf coreopsis, *C. lanceolata* had the highest mean mortality rates under panels (83.3% ± 9.62) (Fig. 17). Mean mortality in control plots was lowest for orange coneflower, *R. fulgida* (0%, however, all were very recent germinants, < 10 d), and *R. hirta* (30.3% +11.81) (Fig. 17). Butterfly milkweed, *A. tuberosa* had the highest mean mortality rates in control plots (79.2% + 14.92) (Fig 17).

4.4 DISCUSSION

In the interest of maximizing the quality of restoration of pollinator habitat, plants chosen for restoration and landscaping should be demonstrably attractive to pollinators as well as successful in establishment on sites with similar soil types and climate (Menz et al. 2011). Of the 13 native plant species evaluated in the greenhouse experiment, *Asclepias tuberosa*, *Conoclinium coelestinum*, *Echinacea purpurea*, *Marshallia obovata, Rudbeckia fulgida*, *Rudbeckia hirta,* and *Stokesia laevis* had mean germination rates in excess of 50% under 90% shade conditions. *Aquilegia canadensis*, *Chrysogonum virginianum*, *Coreopsis lanceolata*, *Gaillardia pulchella*, *Geranium maculatum*, and *Phlox divaricata* had lowest germination rates (<50%) in the greenhouse experiment. Student t-tests indicated there was no significant difference in mean germination rates between shade and control pots in the greenhouse for these 11 of these species (Table 7). This suggests that shade on its own is not a limiting factor for these select native plant establishment on SPFs.

Chrysogonum virginianum, G. maculatum, and P. divaricata each were impacted by mold in the stratification process and this may have affected their germination rates. Additionally, *C. virginianum* germination has been noted as inconsistent and is usually propagated from cuttings (The University of

Texas at Austin Lady Bird Johnson Wildflower Center 2015). Its germination may be improved by removal of seed coat, as recommended anecdotally to me by North Carolina Botanical Garden. Manual removal of the seed coat would be difficult to complete on a large scale, however, making it unsuitable for SPF applications unless chemically treated.

These may not be the only barriers to germination, some species, e.g., *P. divaricata* as well as *G. maculatum*, are noted to have complex germination requirements (Bierzychudek 1982; Mottl et al. 2006). Germination rates of less than 15% have been reported for *Aquilegia canadensis* by other studies as well (Routley et al. 1999; Drayton & Primack 2012). *Coreopsis lanceolata* seeds have previously been shown to have high levels of dormancy, and germination rates of 15% after 25-48 wk of storage at 23% relative humidity under 15°C conditions (Norcini & Aldrich 2007). Germination of *Gaillardia pulchella* in the greenhouse experiment was much less than expected based on reported germination test results (Table 6) and may have been negatively impacted by the field capacity saturation, as it prefers dry, well-drained soils (The University of Texas at Austin Lady Bird Johnson Wildflower Center 2015).

For eight plant of the 13 plant species, the field germination experiment included elements of shade, weed competition, temperature, and hydrological conditions similar to SPFs. The germination rates of the field experiment were much lower than greenhouse results (Table 7). Differences may be due to a number of variables, including moisture and temperature regime in the field, competitive effects, insect or animal consumption, or wind (Schramm 1990). Indian blanket, *G. pulchella* (42.8% $\pm$ 2.87) had the highest mean germination rates under constructed panels, followed by black-eyed Susan, *R. hirta* (21.2% $\pm$ 6.50), eastern purple coneflower, *Echinacea purpurea* (13.5% $\pm$ 1.52), lanceleaf coreopsis, *Coreopsis lanceolata* (12.3% $\pm$ 4.60), and Stokes' aster, *Stokesia laevis* (9.8% $\pm$ 2.63) (Fig. 15).

From these results, and their performance in the pollinator attractiveness study (Table 8), these five natives show promise for use on SPFs. They have ability to germinate and establish in a short time period (less than 3 mo when planted in fall) both under and outside of constructed panels in eastern North Carolina. In particular, *G. pulchella* and *R. hirta* were the fastest growing of the eight species tested, and *G. pulchella* began flowering in both control and shade plots in May 2019. Other restoration efforts and agricultural studies also have reported successes using these native species (Nuzzo 1976; Callan & Kennedy 1995; Sabre et al. 1996; Simmons 2005; Hilbert & Ionta 2015). In one Wisconsin highway

restoration project, *R. hirta* was described having excellent survival rates (Nuzzo 1976). Similarly, in a landfill restoration project in Virginia, *C. lanceolata* had 100% survival of transplants after two years (Sabre et al. 1996). In restoration of a Florida bay, G. pulchella was planted and reported to have persisted ten years after initial planting (Hilbert & Ionta 2015). Interestingly, an agricultural study reported the success of *S. laevis* under unshaded and deep shade conditions (>120 μmol $m^{-2}s^{-1}$). Also, *E. purpurea* is reported as a having long-term success in prairie plantings in Illinois (Schramm 1990). Additionally, other attributes of *G. pulchella* and *R. hirta* may contribute to their success in native plant landscaping. *G. pulchella* can help in the suppression of invasive annuals (Simmons 2005), and *R. hirta* has been described as rapidly growing (Nuzzo 1976).

Asclepias tuberosa, *Conoclinium coelestinum*, and *Rudbeckia fulgida* could also be used to increase diversity on SPFs, while being expected to be present in smaller numbers, or slow to establish. While *R. fulgida* did not germinate well under the constructed panels, it germinated relatively well in control plots during mid-April (12.8% $\pm$ 2.88). *Marshallia obovata* showed promise for shade germination in the greenhouse experiment and could also be a possible SPF seed mix candidate.

Differences observed in mean germination in the greenhouse and field experiment highlight the need for further *in-situ* SPF studies in North Carolina. Germination results in the greenhouse were achieved after 7 wks of moist-cold stratification. The seeds sown in the field were subject to more variable temperature and moisture conditions. Native seeds can have long periods of dormancy (Blake 1935). These conditions may not have met the requirements to break dormancy of the natives that germinated poorly in the field (e.g. *Asclepias tuberosa, Conoclinium coelestinum Rudbeckia fulgida*). Mean mortality rates for the duration of the field experiment (Fig. 17) indicate further challenges that these native plants faced during establishment due to competition from weedy plants and microclimate conditions. High germinant mortality in the field largely coincided with frost events. Observed frost related morality provides support for sowing seed mixes with a nurse crop such as rye (Wilson & Gerry 1995). Different land preparation techniques such as tilling and herbicide application have also shown to be beneficial in the establishment of seed mixes (Trusty & Ober 2011; Harmon-Threatt & Chin 2016).

Native seed stock was commercially unavailable for three of our selected species, *Chrysogonum virginianum*, *Marshallia obovata*, and *Stokesia laevis*. This shortage impacted my ability to use *Marshallia*

obovata in field germination tests and required using half as many seeds of *Stokesia laevis* as compared to other species in that experiment. SPF land managers are limited in their potential use of these species until seed production can match the demand required for large scale projects. Advanced planning and communication with seed companies may help to alleviate the mismatch here between supply and demand for many species, however (Broadhurst et al. 2015).

CHAPTER 5: DISCUSSION/RECCOMENDATIONS FOR MANAGEMENT

5.1 ARE THESE NATIVES USEFUL TO POLLINATORS IN NC?

North Carolina planted over 4.6 million acres of agriculture in 2018 (USDA NASS 2018). Agrosystems surrounded by less diverse habitats with few plant species have been shown to have significantly fewer bees than those surrounded by uncultivated lands (Ockinger & Smith 2007). It has been hypothesized that native pollinator declines may be corrected by changing agro-management strategies to facilitate flowering plants in buffer areas (Nicholls & Altieri 2012). Diverse pollinator assemblages require floral diversity in proximity of agrosystems beyond the peak crop flowering periods (Nicholls & Alteiri 2012), and native bee abundance and diversity are significantly related to the amount of surrounding natural area (Kremen et al. 2004). Additionally, projects that facilitate the cultivation of native flora are expected to result in increased pollinator presence (Fukase & Simons 2016). Similar enhancements to diversity of plants beyond traditional turf grasses or gravel in SPFs also enhances bird, bumble bee and butterfly diversity (Montag et al. 2016). Native vegetation of SPFs could also improve the connectivity between natural areas, which may benefit rare or threatened insect species, such as monarch butterflies (Walston et al. 2018).

The ten observed native plant species in the Belk Feed a Bee^{TM} pollinator bed provided multiple floral resources (at least four species were flowering at all times) during the 2018 growing season (Fig. 10). During my observational study (Chapter 3), all ten native plant taxa were visited by insects known to contribute to pollination. A total of 23 genera and at least 35 spp. of insects were observed visiting these native plants during 20 observation days. Similar pollinator studies in North Carolina have reported similar insect diversity visiting plants in urban and planted settings (Rogers et al. 2014; Hamblin et al. 2018). I also would expect an increase in insect diversity at the Belk site through time, as previous studies have described a pattern of increased insect species richness associated with a greater age of native plantings (M'Gonigle et al. 2015).

The visitation index of visits per floral unit (V/F) indicated that native plants *S. laevis*, *C. lanceolata*, and *G. pulchella* were the most attractive to pollinating insects (Table 5). Shannon's Diversity Index (H') was used to describe the diversity of floral visitors among the ten observed native plant species. When ranked using this index, *C. virginianum*, *R. hirta*, and *G. pulchella* were the most attractive, in that order (Table 5). Each of these indices is sensitive to flowering period and plant-insect abundance, e.g.

abundance of insect visitors or number of floral units. For example, *Marshallia obovata* and *Stokesia laevis* have lower indices and appear less attractive when compared to *Chrysogonum virginianum* using Shannon's Diversity Index (H'), which may be due to their small number of floral units (118 and eight compared to 1419 floral units) and the brevity of their bloom periods (Table 7, Fig. 13). Some species show a disparity in their ranks based on these two indices, such as *C. coelestinum* (ranked sixth by H' but tenth by V/F) and *E. purpurea* (ranked fourth by H' and eighth by V/F). While these plant species attracted multiple insect taxa, many of them visited less than four times over the course of the observation period (i.e., *Ceratina* sp., *Euphyes* sp., *Campsomeris* sp., and *Physocephala* sp.). A more complete picture of pollinator usefulness is presented by the combined ranking. When ranks of these two indices were combined, *G. pulchella, C. virginianum*, *C. lanceolata*, and *A. tuberosa* are the most attractive to a diverse community of known pollinators, followed by *R. hirta, S. laevis*, and *E. purpurea* (Table 5). *A. tuberosa*, *C. lanceolata E. purpurea*, *G. pulchella,* and *R.* hirta have been described as attractive to pollinators by other studies as well (Fishbein & Venable 1996; Grundel et al. 2000; Collins & Foré 2009; Buckley 2011; Robson 2014; Tuell et al. 2014). No known studies exist on the pollinator attractiveness of *C. virginianum* or *S. laevis,* but both plant species are described as attractive to pollinators among horticulturists (The University of Texas at Austin Lady Bird Johnson Wildflower Center 2015).

An additional consideration is the abundance of resources provided by these ten native plant species during 2018 observation period. Top floral producers during my 2018 observations were *C. virginianum*, *R. fulgida*, *C. coelestinum*, and *A. tuberosa*, and *E. purpurea* (Table 5). The fewest flowers were produced by *S. laevis*.

Halictus spp., native sweat bees, were the most abundant insects in summer 2018, visiting all ten plant species and representing 72.7% of the visits (Table 3). *Bombus* spp., bumble bees, were the second most abundant visitors (8.7%), followed by syrphid flies in the genus *Toxomerus* (4.1%). *Rudbeckia fulgida, Echinacea purpurea, Gaillardia pulchella*, and *Chrysogonum virginianum* received the majority of visits from these insects (Table 3). Other pollinator studies have noted the abundance of these genera (Tommasi et al. 2004; Subhakar et al. 2011). These insect genera are also known for their usefulness in pollination of agricultural crops (Boyle & Philogene 1982; Kremen et al. 2002). The floral characteristics of these 10 native plants likely play a role in the insects attracted. For example, corolla length of plant species is

associated with their insect visitors (Dlusskii et al. 2004). Another study found that the highest abundance diversity of pollinators were collected in yellow pan traps that were 14.5 mm in diameter and 8.5 mm high (Harris et al. 2017). Plants with longer corollas paired with dark blue or purple inflorescences are known to attract bumble bees (Dlusskii et al. 2004). Short tongued bees, such as those of the genus *Halictus,* are associated with medium-sized corollas, and syrphid flies are associated with shallow corollas of white and yellow flowers (Dlusskii et al. 2004). Moreover, *Bombus* sp. and *Halictus* sp. have been shown to prefer flowers in the family Asteraceae (Abrahamovich et al. 2001; Dikmen et al. 2018). Because of these preferences, a diversity of floral resources can ultimately enhance the diversity of insect groups attracted.

In addition, two correspondence analyses showed significant correlation between these native plants and known pollinator taxa, as well as insect morpho-groups. The second correspondence analysis between these plant species and insect morpho-groups suggests that insect visitation was likely correlated to morphological traits, such as corolla and mouthpart length (Colley & Luna 2000; Dlusskii et al. 2004). As indicated by the inertia contributed to dimensions one and two in both analyses (Fig. 11,12), *E. purpurea* and *C. virginianum* may encourage further diversity, particularly *Bombus* sp. and *Toxomerus* sp., when included in plantings for native pollinators. These two species could be especially useful to conservation biologists with interest in attracting these particular taxa in eastern NC.

This collection of ten native plants was visited by 23 genera of insects. The appeal to insect visitors, as shown by the combined ranking, suggests that primarily the floral resources of *G. pulchella*, *C. virginianum*, *C. lanceolata*, and *A. tuberosa* are driving insect visitation at the Belk site. *Rudbeckia hirta, S. laevis*, and *E. purpurea* are likely also contributing considerably to insect abundance and diversity. These native plants could be useful in providing a framework of resources for a diverse community of native pollinators in restoration projects in eastern NC. Least attractive by the combined ranking were *C. coelestinum*, *R. fulgida*, and *M. obovata* (Table 5). While least attractive when compared to the other observed native plant species, it is worth noting that each attracted multiple species of pollinating insects could provide additional diversity of floral resources in native plantings. For example, *Rhynchospora colorata,* the flowering sedge planted at the Belk site, was visited by pollinating insects from five different insect genera and could be an additional floral resource as well.

Data on pollinator visitation were not collected for four plant taxa in the plots, *A. canadensis*, *G. maculatum*, *P. divaricata* (due to early blooming; February-April), and *S. canadensis*, (which did not flower) because of limited flowering during the observational period. While it was not suitable to include them in the observational study, it is important to include similar early-blooming species to ensure resources are available early in the growing season to nourish developing insect larvae (Mattila & Otis 2006).

Although insect visitation was observed in shaded plots in the landscaped bed near the Belk building, it is still unclear whether native plants will attract an abundance of pollinators under actual PV panel arrays. Light environment affects pollinator assemblages and pollination has been noted to be a limiting factor in understory plant success (Grubb 2015; Cole et al. 2017). Nonetheless, my results demonstrate that native plants, even relatively few taxa, used in landscaping on human-modified environments can help support biodiversity of native insect pollinators.

5.2 ARE THESE NATIVES SUITABLE FOR LANDSCAPING EASTERN NC SOLAR FARMS?

Solar panel farms (SPFs) are distinctive sites for restoration and support of native biodiversity. While PVs reduce radiation available for photosynthesis by between 80-92% (See Chapter 2, Armstrong et al. 2016), PV panel arrays may offer favorable temperature conditions for shade tolerant species during the hot, dry summers of the coastal plain (Geiger 1954). Additionally, plant species under the panels are expected to experience less water stress, which could partially counteract effects of limited PAR availability (Givinish 1988; Valladares et al. 2016). These nuanced microclimate conditions make predicting plant success difficult. Further complicating this, information about natives in landscaping application is still lacking for many plant species. This lack of information hinders landscape managers who might consider selecting natives in their projects (Lubell 2017). There is also some work to be done on tracking provenance, ecotype, and cultivar information (Vogel et al. 2005). Another concern with natives is that ecological function may be altered when plant species are bred (in horticultural form, Kramer et al. 2019).

In this study I was able to determine that several native species are readily germinable and able to survive these microsites in eastern North Carolina, specifically: Indian blanket, *Gaillardia pulchella,* black-eyed Susan, *Rudbeckia hirta,* eastern purple coneflower, *Echinacea purpurea,* lanceleaf coreopsis, *Coreopsis lanceolata,* and Stokes' aster, *Stokesia laevis* (Fig. 15). Of the 13 evaluated, these five natives show the most promise for use on SPFs. They have ability to germinate and establish in a short time period

with no supplemental water or fertilizer (less than 3 mo when planted in fall) both under and outside of constructed panels. Not only will these species germinate in eastern North Carolina, but they rank well in pollinator attractiveness, inflorescence production, and mortality rates among the 13 native species compared (Table 8).

In particular, *G. pulchella* and *R. hirta* were the fastest growing of the eight species tested in the field. These results support what others have reported regarding the successes of these natives (Nuzzo 1976; Schramm 1990; Callan & Kennedy 1995; Sabre et al. 1996; Simmons 2005; Hilbert & Ionta 2015). Additionally, *G. pulchella* has been described for its usefulness in the suppression of invasive annuals (Simmons 2005). *Rudbeckia hirta* has also been previously described as rapidly growing (Nuzzo 1976), which may help it compete against weedy species. These other published results also argue for longer term field studies of these native plant species to evaluate their ability to suppress weeds. The germination of *G. pulchella* may have been inhibited in the greenhouse due to moist environment. The field experiment results for *G. pulchella* exceeded germination results, providing support for this hypothesis. *Marshallia obovata* was not used in the final germination experiment due seed shortage, however, it performed well in the greenhouse germination experiment and merits further consideration for use in restoration.

Each solar company will need to plan vegetation based on individual site characteristics and management strategies. Solar farm managers must choose whether to seed the entire SPF with one seed mix, include plantings in buffer areas, avoiding PV panel arrays, or plant the perimeter (NCPCA 2018; Semeraro et al. 2018). The natives chosen should align with these needs, taking plant habitat preference and height into account. Successful seed mixes should ultimately contain fast establishing forbs, grasses, as well as perennials that can outcompete aggressive weeds (Schramm 1990). Initially fast-growing forbs such as *G. pulchella* and *R. hirta* and grasses are needed to reduce weedy invasion during establishment. These initial plants are followed by native forbs which are slow to establish (Schramm 1990), such as *A. tuberosa*, *C. coelestinum*, and *R. fulgida.* Additionally, the native shrubs *Rhododendron catawbiense*, *Ilex glabra*, and *Leucothoe racemosa* were observed receiving visits from insects, and also could be useful in SPF perimeter plantings to provide additional floral and habitat resources.

Low germination rates in the field of species that performed well in the greenhouse (*A. tuberosa*, *C. coelestinum*, and *R. fulgida,* Fig 7) show limitations of greenhouse experiments when evaluating natives for

restoration applications. The differences in germination could be due to site characteristics, seasonal weather, or competition effects. It is likely that because seeds sown in the field had variable temperature and moisture conditions, dormancy might not have been broken for some poor performing species (e.g. *Asclepias tuberosa, Conoclinium coelestinum, Rudbeckia fulgida*). Additional practices could be adopted to increase germination success. Previous researchers have found planting season (November-February) and the use of herbicide prior to planting result in the best establishment of native seed mixes (Trusty & Ober 2011; Threatt & Chin 2016). Also, locally adapted native seed has been shown to increase plant species richness more than land preparation techniques on their own (Falk et al. 2013). My field germination experiment highlighted another challenge that native plants face in establishment under conditions similar to SPFs in eastern North Carolina. Apparent frost mortality was particularly high for the species that germinated during winter, even under the cover of constructed panels. These results provide support for recommendations of a winter rye or similar nurse crop as seedlings become established (Beatty et al 2017).

Although not included in my germination experiments, *Sanguinaria canadensis* has been shown to have persistence potential in restoration. In a 15-yr study involving eight perennial plants, *S. canadensis* was the only species to establish and persist in shaded restoration plots (Drayton & Primack 2012). However, the ability of this shade tolerant forest understory ephemeral to establish in the coastal plain of eastern NC is unlikely. Also, due to its double dormancy, it would likely not be suitable for solar farm seed mixes.

Further development of native seed stocks will help to provide more options for SPF land managers, particularly for *Marshallia obovata* and *Stokesia laevis*, which are limited in their commercial availability. The data presented in this work are a starting point to understanding how NC native perennials perform on SPFs. More *in-situ* studies that incorporate the effect of cover crops on successful establishment of native plants also are needed to better inform SPF landscape managers. Ultimately, the use of native plants for landscaping on SPFs remains a promising option for promotion and maintenance of both plant and insect biodiversity on these and other human-modified landscapes.

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Table 1: Fourteen native perennial plant species were planted in pollinator observation beds. Species available as seed were used in germination experiments.

Species[1]	Common Name[1]	Bloom Period[2]	Height[2] (in./cm)	Light Preference[3]
Aquilegia canadensis L.	red columbine	spring (M,A,M)	32/80	part shade/part sun
Asclepias tuberosa L. spp. *tuberosa*	butterfly milkweed	summer (M,J,J,A)	32/80	part sun/sun
Chrysogonum virginianum L. var. *virginianum*	green and gold	spring (M,A,M,J)	16/40	shade/part sun
Conoclinium coelestinum (L.) D.C.	blue mistflower	late summer-frost (J,A,S,O)	39/100	part shade/part sun
Coreopsis lanceolata L.	lanceleaf tickseed	spring (A,M,J)	39/100	sun/part shade
Echinacea purpurea var. purpurea L. Moench (Kim's Kneehigh)	eastern purple coneflower	late spring-summer (M,J,J)	39/100	sun/part shade
Gaillardia pulchella Foug.	Indian blanket	spring-late fall (A,M,J,J,A,S,O)	24/60*	sun/part shade
Geranium maculatum L.	spotted geranium	spring (A,M,J)	24/60	part shade/part sun
Marshallia obovata (Walter) Beadle & F.E. Boynt. var. *obovata*	spoonshape Barbara's buttons	spring (A,M)	28/70	part shade/part sun
Phlox divaricata L.	wild blue phlox	spring (A)	20/50	shade/part sun
Rudbeckia fulgida Aiton.	orange coneflower	fall (A,S,O)	47/120	sun/part shade
Rudbeckia hirta L.	black-eyed Susan	late spring-summer (M,J,J)	39/100	sun/ part shade
Sanguinaria canadensis L.[4]	bloodroot	spring (M,A)	16/40	shade/part shade
Stokesia laevis (Hill) Greene.	Stokes' aster	summer (J,J,A)	28/70	part sun/sun

[1] Taxonomy and common names follow USDA NRCS (2017).

[2] Bloom periods in the Carolinas and height from Radford et al. (1968) or USDA NRCS (2017) for *G. pulchella*.

[3] Light preferences from Mellichamp (2014), The University of Texas at Austin Lady Bird Johnson Wildflower Center (2015), NCSU Extension (2017), and USDA NRCS (2017).

[4] Double stratification required and recalcitrant germination; will not be used for germination studies.

Table 2: Pollinator benefits and known pollinators (regionally or otherwise) of 14 native species.

Plant Species	Benefits for Pollinators[1]	Known Insect Visitors[2]
Aquilegia canadensis	early bloomer, nectar, Lepidoptera larval host	Lepidoptera
Asclepias tuberosa	nectar, Lepidoptera larval host	Hymenoptera (Apidae), Lepidoptera (Fishbein & Venable 1996)
Chrysogonum virginianum	nectar	Lepidoptera
Conoclinium coelestinum	nectar	Lepidoptera
Coreopsis lanceolata	nectar	Lepidoptera (Grundel et al. 2000)
Echinacea purpurea	nectar	Hymenoptera (Apidae, Halictidae, Nomadinae, Scoliidae, Sphecidae), Lepidoptera (Collins & Foré 2009)
Gaillardia pulchella.	nectar	Lepidoptera (The University of Texas at Austin Lady Bird Johnson Wildflower Center 2015)
Geranium maculatum	nectar	Diptera (Syrphidae), Hymenoptera (Adrenidae, Apidae, Halictidae, Megachilidae, Nomadinae), Lepidoptera (McKinney & Goodell 2010).
Marshallia obovata	early bloomer	Lepidoptera
Phlox divaricata	nectar	Diptera (Bombyliidae), Lepidoptera (Wiggam & Ferguson 2005)
Rudbeckia fulgida	nectar	Diptera (Syrphidae), Hymenoptera (Apidae, Halictidae), Lepidoptera (Scott & Molano-Flores 2007).
Rudbeckia hirta	larval host for bordered patch and gorgone checkerspot butterflies	Lepidoptera (Grundel et al. 2000)
Sanguinaria canadensis	early bloomer	Hymenoptera (Apidae) (Motten 1986)
Stokesia laevis	nectar	Lepidoptera

[1] Pollinator benefits originated from The University of Texas at Austin Lady Bird Johnson Wildflower Center (2015).

[2] Observed pollinator information for North Carolina originated from NCSU Extension (2017) and NC Audubon (2017).

Table 3: Insect visitation frequency for ten native plant species during 10-min plot observations at the Belk Bayer Feed-A-Bee™ site in 2018.

Insect taxa / Plant Species	*Ammophila* sp.	*Apis mellifera*	*Augochlorini*	*Bombus* sp.	*Bombylius* sp.	*Campsomeris* sp.	*Ceratina* sp.	*Erynnis* sp.	*Euphyes* sp.	*Euodynerus* sp.	*Halictus* sp.	*Hylephila* sp.	*Lasioglossum* sp.	*Megachile* sp.	*Melissodes* sp.	*Palpada* sp.	*Physocephala* sp.	*Sceliphron* sp.	*Scolia* sp.	*Stelis* sp.	*Strymon* sp.	*Toxomerus* sp.	*Xylocopa* sp.
Asclepias tuberosa	5	-	12	2	-	-	-	-	-	-	228	-	3	68	-	-	-	-	-	-	-	-	-
Chrysoganum virginianum	6	1	35	-	14	-	-	1	-	-	263	-	45	-	-	-	-	-	-	-	-	69	-
Conoclinium coelestinum	-	-	-	-	-	4	-	-	-	-	63	6	-	-	-	4	2	1	-	-	-	-	-
Coreopsis lanceolata	-	5	-	15	-	-	-	-	-	4	188	1	2	-	-	-	-	-	-	-	-	2	-
Echinacea purpurea	-	-	-	110	-	-	2	-	4	8	27	-	-	-	-	-	-	-	-	-	3	-	-
Gaillardia pulchella	1	-	-	35	-	-	-	-	-	3	125	-	3	-	4	-	-	-	2	-	-	8	1
Marshallia obovata	-	-	-	1	-	-	-	-	-	-	35	-	1	-	-	-	-	-	-	-	-	2	-
Rudbeckia fulgida	1	-	-	-	-	-	-	2	-	1	430	1	4	-	-	2	-	-	-	9	-	-	-
Rudbeckia hirta	-	4	1	1	-	1	-	1	-	-	24	-	-	-	-	-	-	-	2	1	-	-	-
Stokesia laevis	-	-	-	3	-	-	-	-	-	-	24	-	-	-	-	-	-	-	-	-	-	-	-
Total Plants Visited	4	3	3	7	1	2	1	3	1	4	10	3	6	1	1	2	1	1	2	2	1	4	1
Total Visits	13	10	48	167	14	5	2	4	4	16	1,407	8	58	68	4	6	2	1	4	10	3	81	1
% of Total Visits	0.67%	0.52%	2.48%	8.63%	0.72%	0.26%	0.10%	0.21%	0.21%	0.83%	72.71%	0.41%	3.0%	3.51%	0.21%	0.31%	0.10%	0.05%	0.21%	0.52%	0.16%	4.13%	0.05%

Table 4: Insect visitation of ten native plant species during the 20 observation days at the ECU Belk Bayer Feed-A-Bee™ site in 2018.

Insect Taxa / Date	*Ammophila* sp.	*Apis mellifera*	*Augochlorini*	*Bombus* sp.	*Bombylius* sp.	*Campsomeris* sp.	*Ceratina* sp.	*Erynnis* sp.	*Euodynerus* sp.	*Euphyes* sp.	*Halictus* sp.	*Hylephila* sp.	*Lasioglossum* sp.	*Megachile* sp.	*Melissodes* sp.	*Palpada* sp.	*Physocephala sp.*	*Sceliphron* sp.	*Scolia* sp.	*Stelis* sp.	*Strymon* sp.	*Toxomerus* sp.	*Xylocopa sp.*
5/5/2018				X	X						X		X										
5/16/2018											X								X			X	
5/23/2018				X					X		X		X									X	
6/1/2018			X		X						X											X	
6/6/2018		X		X							X		X	X						X		X	
6/13/2018			X	X				X			X		X									X	
6/18/2018				X			X		X		X												
6/27/2018			X	X					X		X		X		X						X		
7/4/2018				X		X	X		X	X	X		X									X	X
7/10/2018				X							X	X	X		X	X							
7/19/2018			X	X							X									X			
7/26/2018	X			X							X												
8/6/2018	X			X							X						X	X					
8/15/2018								X			X	X	X			X		X					
8/25/2018				X							X												
9/4/2018			X	X							X		X										
9/9/2018											X												

Table 5: Pollinator visitation metrics for ten native plant species in the ECU Belk Bayer Feed-A-Bee™ site from 1,935 observed insect visits between May and September 2018. F = total observed floral units per species defined as number of open flowers or flowering heads (Asteraceae), V = number of insect visits per species, visitation index = insect visits divided by number of floral units (V/F), S = species richness of visiting insects, H' = Shannon's diversity index of visiting pollinators, and rankings of plant species based on the visitation index (V/F), the diversity index (H'), and a combined rank of overall attractiveness (sums of the H' and V/F ranks).

Plant Species	Floral Units (F)	Insect Visits (V)	Visitation Index (V/F)	Species Richness (S)	Shannon's Diversity Index (H')	V/F Ranking	H' Ranking	Combined Rank
Asclepias tuberosa	752	318	0.42	6	0.83	4	5	3.5
Chrysogonum virginianum	1419	433	0.31	8	1.22	7	1	2
Conoclinium coelestinum	810	80	0.10	5	0.83	10	6	9
Coreopsis lanceolata	217	217	1.00	7	0.58	2	7	3.5
Echinacea purpurea	518	154	0.30	6	0.93	8	4	6
Gaillardia pulchella	400	182	0.46	8	1.03	3	3	1
Marshallia obovata	118	39	0.33	4	0.44	6	8	7
Rudbeckia fulgida	1110	450	0.41	8	0.25	5	10	8
Rudbeckia hirta	181	35	0.19	8	1.18	9	2	5
Stokesia laevis	8	27	3.38	2	0.35	1	9	4

Table 6: Germination experiment seed sources, reported germination rates, date of test, and reported percent live seed. Germinability not provided for *E. purpurea, R. hirta, C. virginianum, M. obovata,* and *S. laevis.*

Native Plant Species	Seed Source	Provenance	Reported Germination (%)	Year of Germination Test	% Live Seed
Aquilegia canadensis	Prairiemoon	MN	25	2017	71.25
Asclepias tuberosa	Prairiemoon	MN	25	2017	71.25
Chrysogonum virginianum	NC Botanical Garden	NC			
Conoclinium coelestinum	Prairiemoon	MN	25	2017	71.25
Coreopsis lanceolata	Prairiemoon	WI	25	2017	71.25
Echinacea purpurea	Prairiemoon	Upper Midwest			98.44
Gaillardia pulchella	American Meadows	CA	74	2017	
Geranium maculatum	Prairiemoon	WI	25	2017	71.25
Phlox divaricata	Prairiemoon	WI	25	2017	71.25
Marshallia obovata	NC Botanical Garden	NC			94.45
Rudbeckia fulgida	Prairiemoon	IL	25	2017	71.25
Rudbeckia hirta	Prairiemoon	MN			
Stokesia laevis	NC Botanical Garden	NC			

Table 7: Mean percent germination results compared for greenhouse and field experiments. Student t-test results for 13 native plant species in the greenhouse germination experiment to test the null hypothesis that mean germination in the shade treatment is not different from the control pots based on counts of germinants (50 seeds per pot, five replicate pots). Student t-tests were not performed for *Chrysogonum virginianum, Phlox divaricata,* or the field experiment due to low germination rates. All species compared had equal variances, except *Gaillardia pulchella.*

Plant Species	Greenhouse Germination (%) Mean ± SE		t-statistic	df	p-value	Field Germination (%) Mean ± SE	
	Shade	Unshaded (Control)				Shade	Unshaded (Control)
Aquilegia canadensis	6.0 ± 0.84	2.4 ± 1.10	1.62	8	0.1447	n/a	n/a
Asclepias tuberosa	85.6 ± 1.24	88.4 ± 0.97	.89	8	0.3999	7.8 ± 4.42	4.8 ± 1.25
Chrysogonum virginianum	2.4 ± 0.58	0	2.06	n/a	n/a	n/a	n/a
Conoclinium coelestinum	50.8 ± 2.71	40.8 ± 2.16	1.44	8	0.1872	2.5 ± 1.18	3.3 ± 1.63
Coreopsis lanceolata	32.4 ± 2.22	22.0 ± 1.52	1.93	8	0.0894	12.3 ± 4.60	4.2 ± 1.72
Echinacea purpurea	90.0 ± 0.89	94.4 ± 0.52	2.27	8	0.0530	13.5 ± 1.52	13.7 ± 3.28
Gaillardia pulchella	22.8 ± 0.68	19.2 ± 2.11	0.81	4.8164	0.4553	42.8 ± 2.87	39.0 ± 4.44
Geranium maculatum	2.8 ± 1.15	0.8 ± 0.37	1.54	8	0.1614	n/a	n/a
Marshallia obovata	80.0 ± 0.71	76.8 ± 1.12	1.14	8	0.2861	n/a	n/a
Phlox divaricata	0	0	n/a	n/a	n/a	n/a	n/a
Rudbeckia fulgida	86.4 ± 1.39	81.2 ± 1.99	1.07	8	0.3157	2.2 ± 0.79	12.8 ± 2.88
Rudbeckia hirta	69.6 ± 1.93	72.4 ± 1.36	0.59	8	0.5698	21.2 ± 6.50	12.5 ± 4.11
Stokesia laevis	88.0 ± 1.92	88.8 ± 0.83	0.19	8	0.8561	9.8 ± 2.63	10.7 ± 5.87

Table 8: Summary of ecological characteristics of select native plant taxa for landscaping on eastern North Carolina solar panel farms from this study.

Native Plant Species	Observed Flowering Period	Floral Display (#flowers or heads)	Pollinator Richness	Pollinator Attraction Combined Rank	Germinability in Greenhouse (Shaded)	Germinability in Field (Shaded)	Winter Mortality
Aquilegia canadensis	March-April	n/a	n/a	n/a	Very Low (6.0%))	n/a	n/a
Asclepias tuberosa	June-September	Moderate (752)	Moderate (6)	High (3.5)	High (85.6%)	Very Low (7.8%)	High (78.2%)
Chrysogonum virginianum	April-September	High (1419)	High (8)	High (2)	Very Low (2.4%)	n/a	n/a
Conoclinium coelestinum	July-September	Moderate (810)	Moderate (5)	Low (9)	Moderate (50.8%)	Very Low (2.5%)	Moderate (50.0%)
Coreopsis lanceolata	May-September	Low (217)	High (7)	High (3.5)	Moderate (32.4%)	Low (12.3%)	High (83.3%)
Echinacea purpurea	April-September	Moderate (518)	Moderate (6)	Moderate (6)	High (90.0%)	Low (13.5%)	Moderate (56.2%)
Gaillardia pulchella	April-September	Moderate (400)	High (8)	High (1)	Low (22.8%)	Moderate (42.8%)	Moderate (41.5%)
Geranium maculatum	March-April	n/a	n/a	n/a	Very Low (2.8%)	n/a	n/a
Phlox divaricata	February-April	n/a	n/a	n/a	Very Low (0%)	n/a	n/a
Marshallia obovata	April-May	Low (118)	Moderate (4)	Low (7)	High (80.0%)	n/a	n/a
Rudbeckia fulgida	June-September	High (1110)	High (8)	Low (8)	High (86.4%)	Very Low (2.2%)	High (71.7%)
Rudbeckia hirta	May-August	Very Low (35)	High (8)	Moderate (5)	Moderate (69.6%)	Moderate (21.2%)	Moderate (30.5%)
Stokesia laevis	June-August	Very Low (27)	Low (2)	Moderate (4)	High (88%)	Low (9.8%)	Moderate (42.3%)

Fig. 1: Constructed simulated solar panels in Pitt Co., NC. The panel dimensions are 4.5 m x 1.5 m, the approximate size of a row of five individual panels typical on a SPF.

Fig. 2: Apogee® light meter Model MQ-200 quantum sensor attached with Velcro® to a 60 cm section of 10 cm x 2.5 cm plank for uniform angle of incidence among sensors.

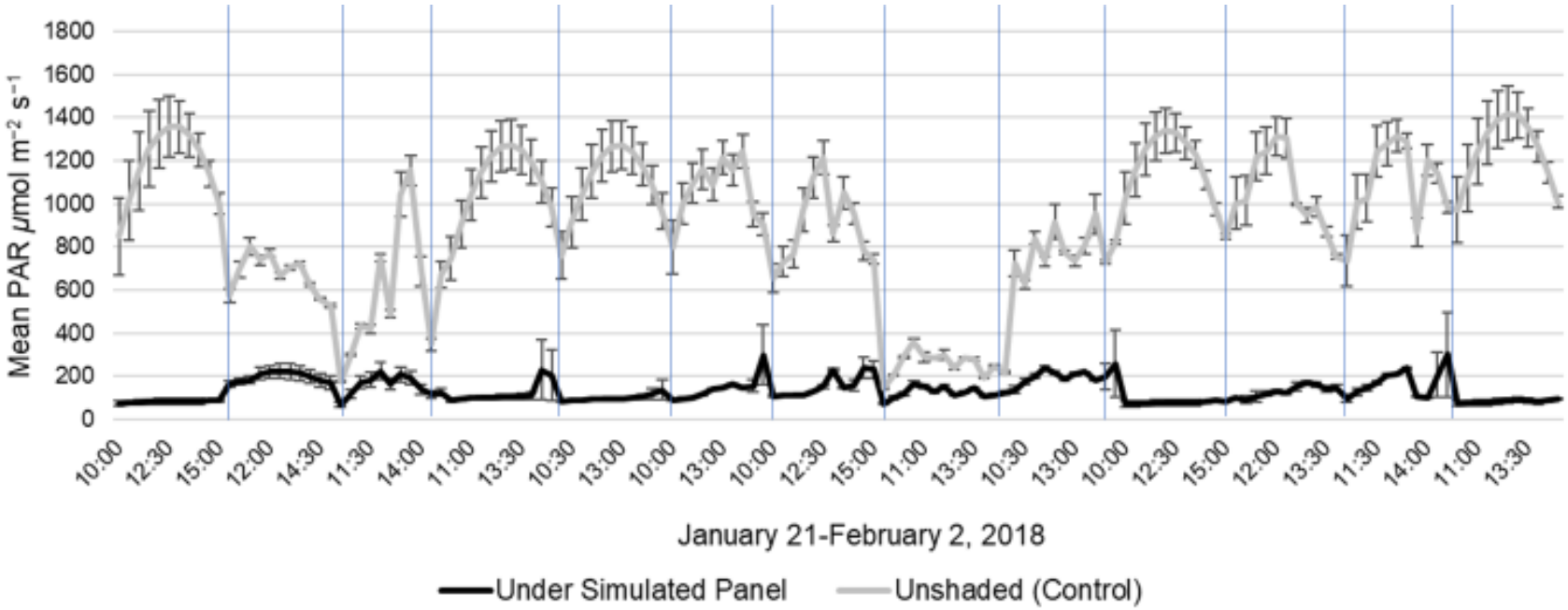


Fig. 3: Winter mean photosynthetically active radiation (PAR) recorded under (black line) and outside of (gray line) a simulated photovoltaic (PV) panel array in Pitt County, NC during peak daylight hours (10:00 to 15:00). Means (± SE) were calculated every 30 mins from three different sensors. The vertical lines on the graph indicate breaks among days between July 12-25.

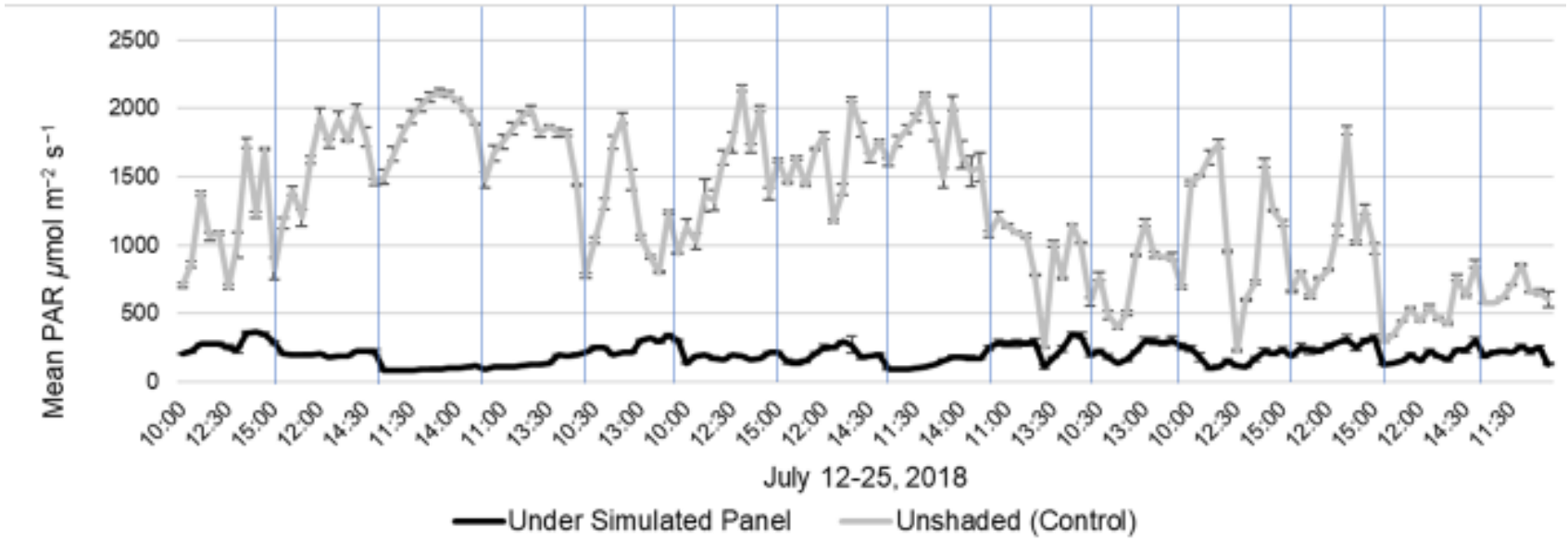


Fig. 4: Summer mean photosynthetically active radiation (PAR) recorded recorded under (black line) and outside of (gray line) a photovoltaic (PV) panel array in Pitt County, NC during peak daylight hours (10:00 to 15:00). Means (± SE) were calculated every 30 mins from three different sensors. The vertical lines on the graph indicate breaks among days between July 12-25.

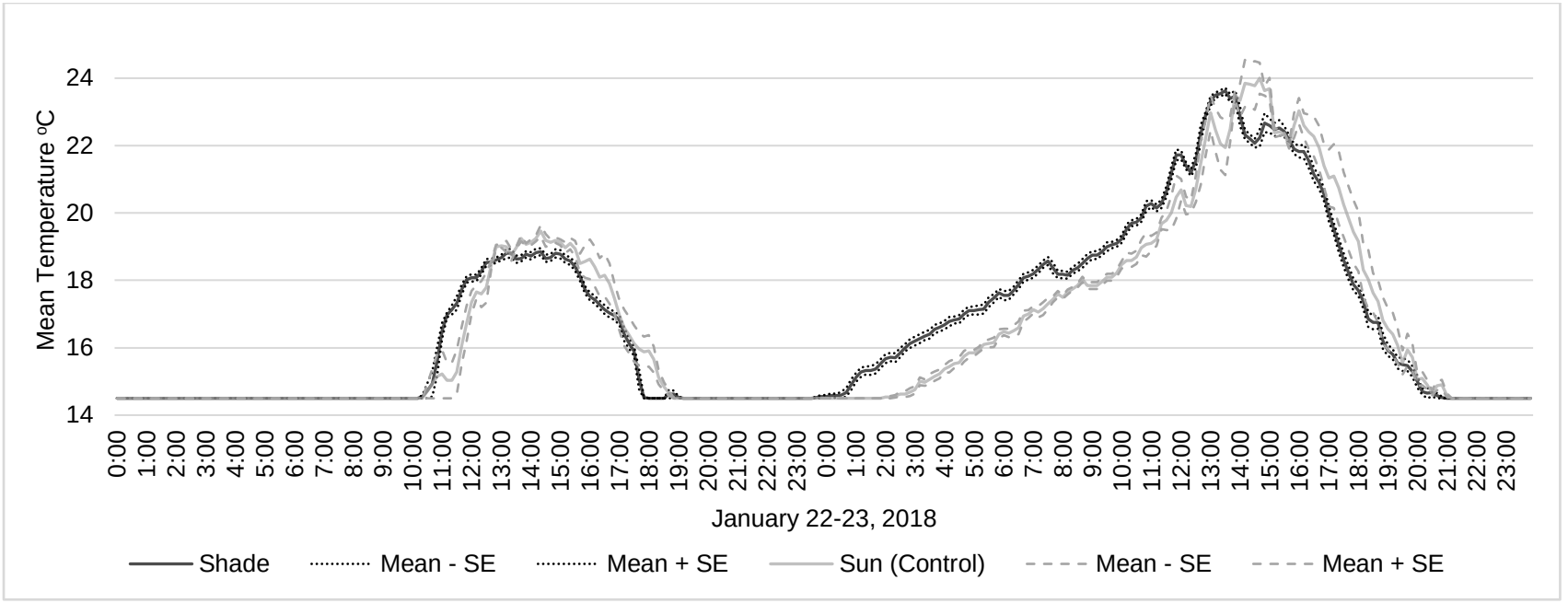


Fig. 5: Example of winter variation in mean air temperatures under vs. outside a simulated photovoltaic (PV) panel array in Pitt County, NC. Upper and lower limits of the standard error (SE) for these mean measurements are included as individual series. One iButton® failed to record, there were ultimately four replicated measurements.

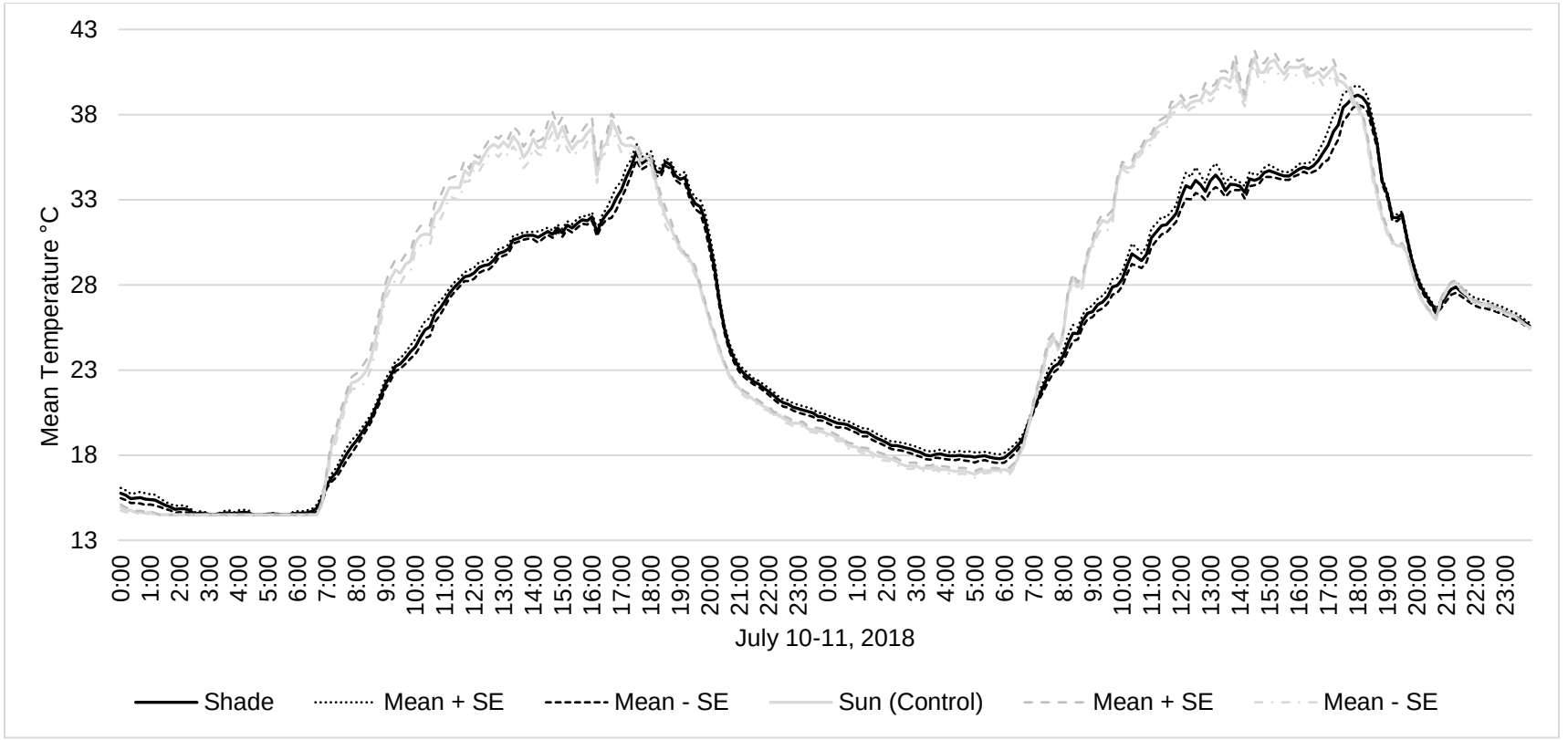


Fig. 6: Example of summer variation in mean air temperatures under vs. outside a simulated photovoltaic (PV) panel array in Pitt County, NC. Upper and lower limits of the standard error (SE) for these mean measurements are included as individual series. Means and SE were calculated from five replicated measurements.

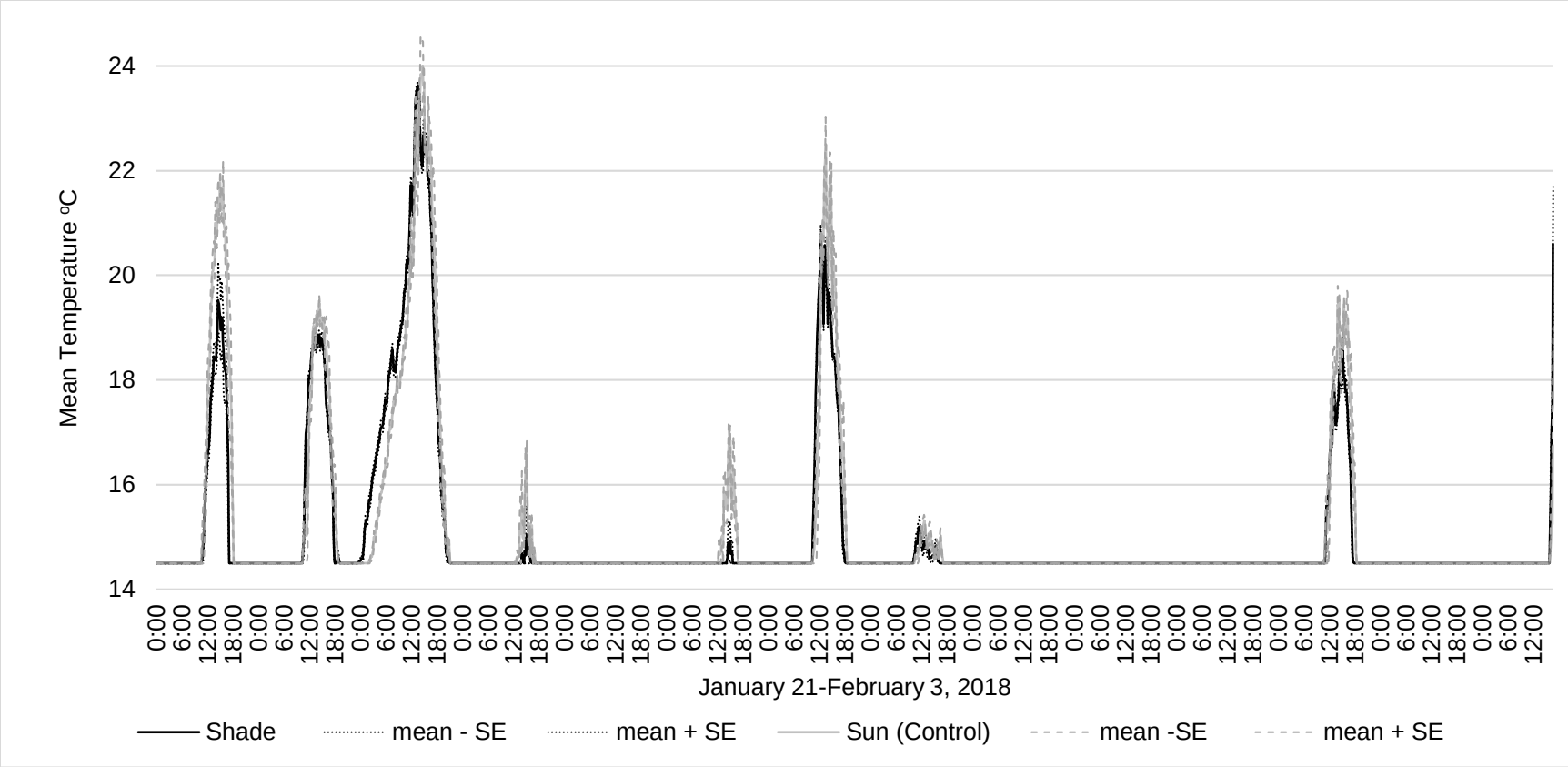


Fig. 7: Winter mean air temperatures under vs. outside a simulated photovoltaic (PV) panel array in Pitt County, NC between January 21-February 3, 2018. Upper and lower limits of the standard error (SE) for these mean measurements are included as individual series. One iButton® failed to record, there were ultimately four replicated measurements.

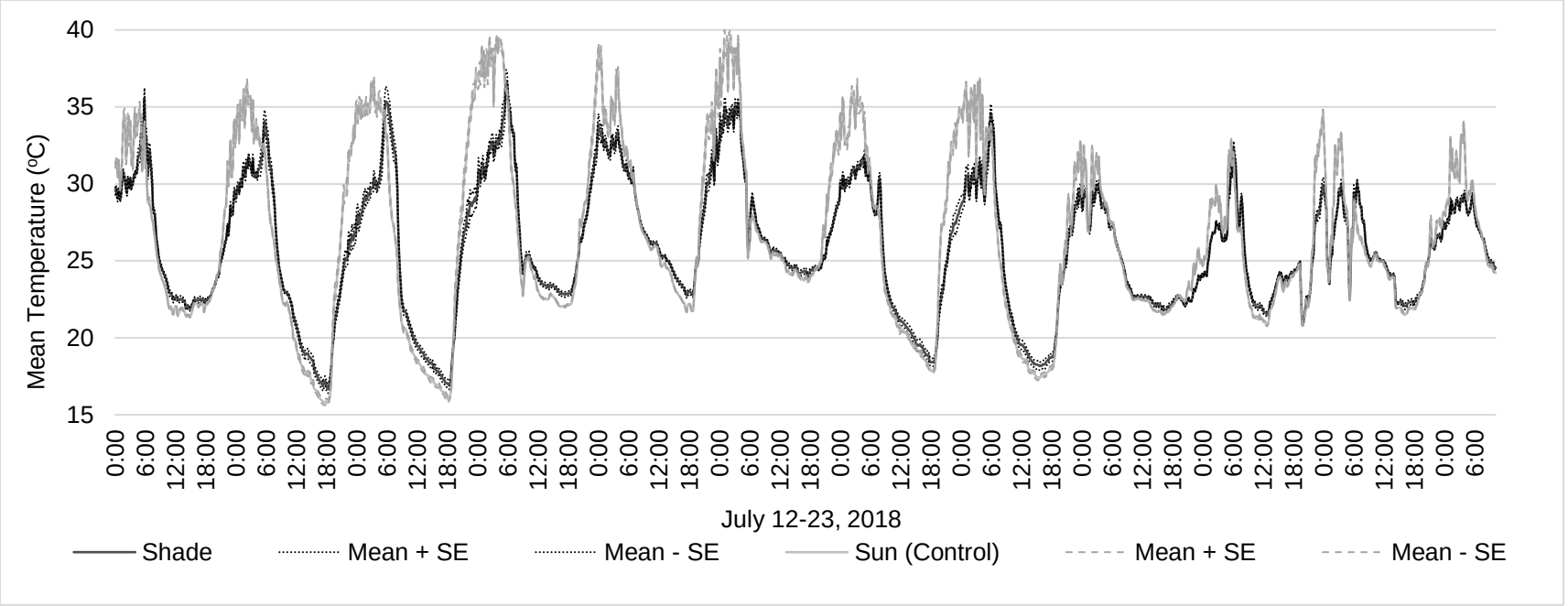


Fig. 8: Summer mean air temperatures under vs. outside a simulated photovoltaic (PV) panel array in Pitt County, NC between July 12-July 23, 2018. Upper and lower limits of SE for these mean measurements are included as individual series. Means and SE were calculated from five replicated measurements.

Fig. 9: Belk Feed a Bee™ landscaped pollinator site established in October 2017 on East Carolina University Campus. This site features 11 native perennial forb species, two native graminoid species, and three native shrub species. Photo credit: Cliff Hollis.

Fig. 10: Lake Laupus Feed a Bee™ landscaped pollinator site established in November 2017 on ECU's West Campus. This site features seven native perennial forb species, two native graminoid species, and three native shrub species.

Pollinator Species

1-*Ammophila* sp.	5-*Bombylius* sp.	9-*Euphyes* sp.	13-*Lasioglossum* sp.	17-*Physocephala* sp.	21-*Strymon* sp.
2-*Apis mellifera*	6-*Campsomeris* sp.	10-*Euodynerus* sp.	14-*Megachile* sp.	18-*Sceliphron* sp.	22-*Toxomerus* sp.
3-*Augochlorini* sp.	7-*Ceratina* sp.	11-*Halictus* sp.	15-*Melissodes* sp.	19-*Scolia* sp.	23-*Xylocopa* sp.
4-*Bombus* sp.	8-*Erynnis* sp.	12-*Hylephila* sp.	16-*Palpada* sp.	20-*Stelis* sp.	

Plant Species

1-*Asclepias tuberosa*
2-*Chrysogonum virginianum*
3-*Conoclinium coelestinum*
4-*Coreopsis lanceolata*
5-*Echinacea purpurea*
6-*Gaillardia pulchella*
7-*Marshallia obovata*
8-*Rudbeckia fulgida*
9-*Rudbeckia hirta*
10-*Stokesia laevis*

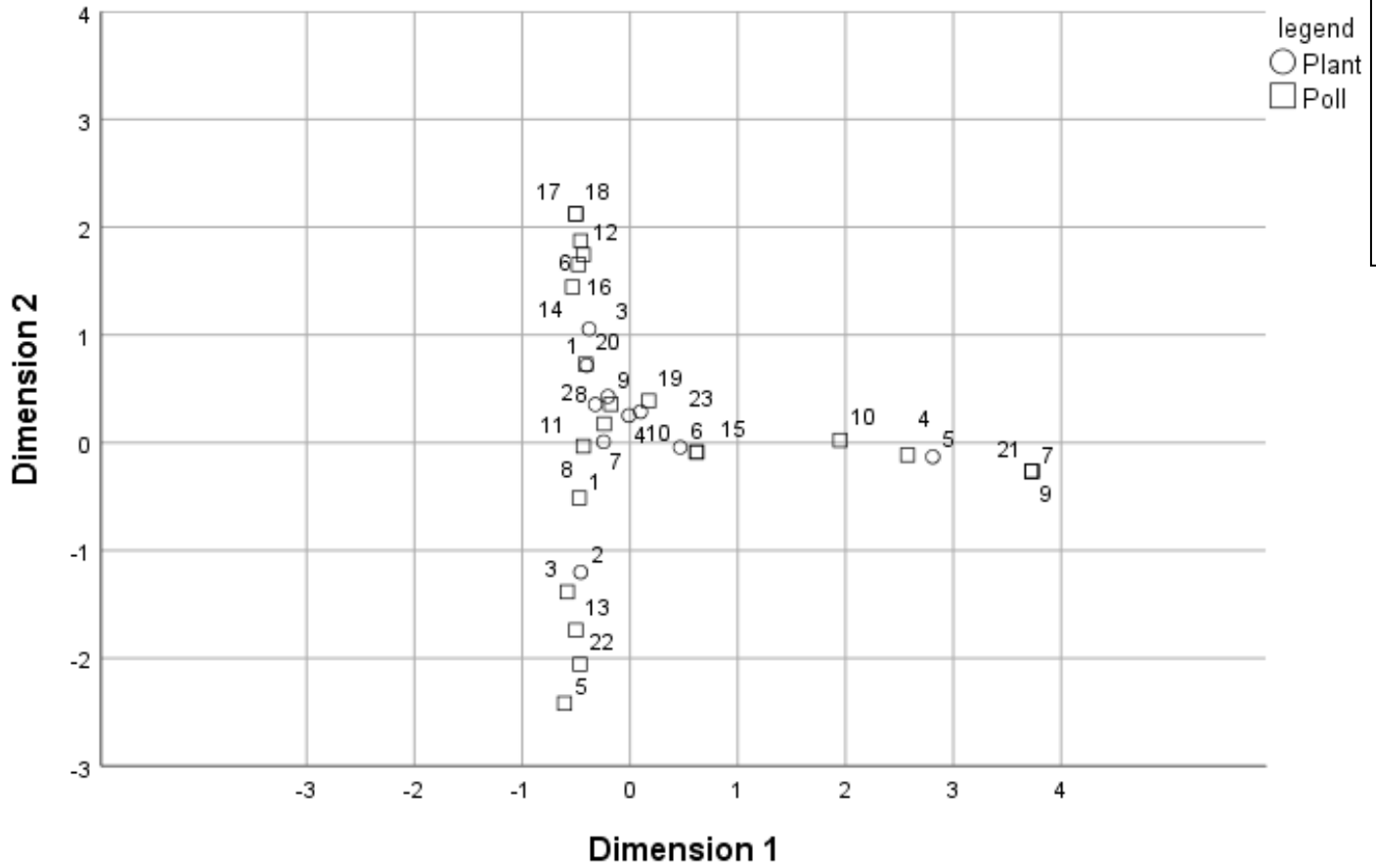
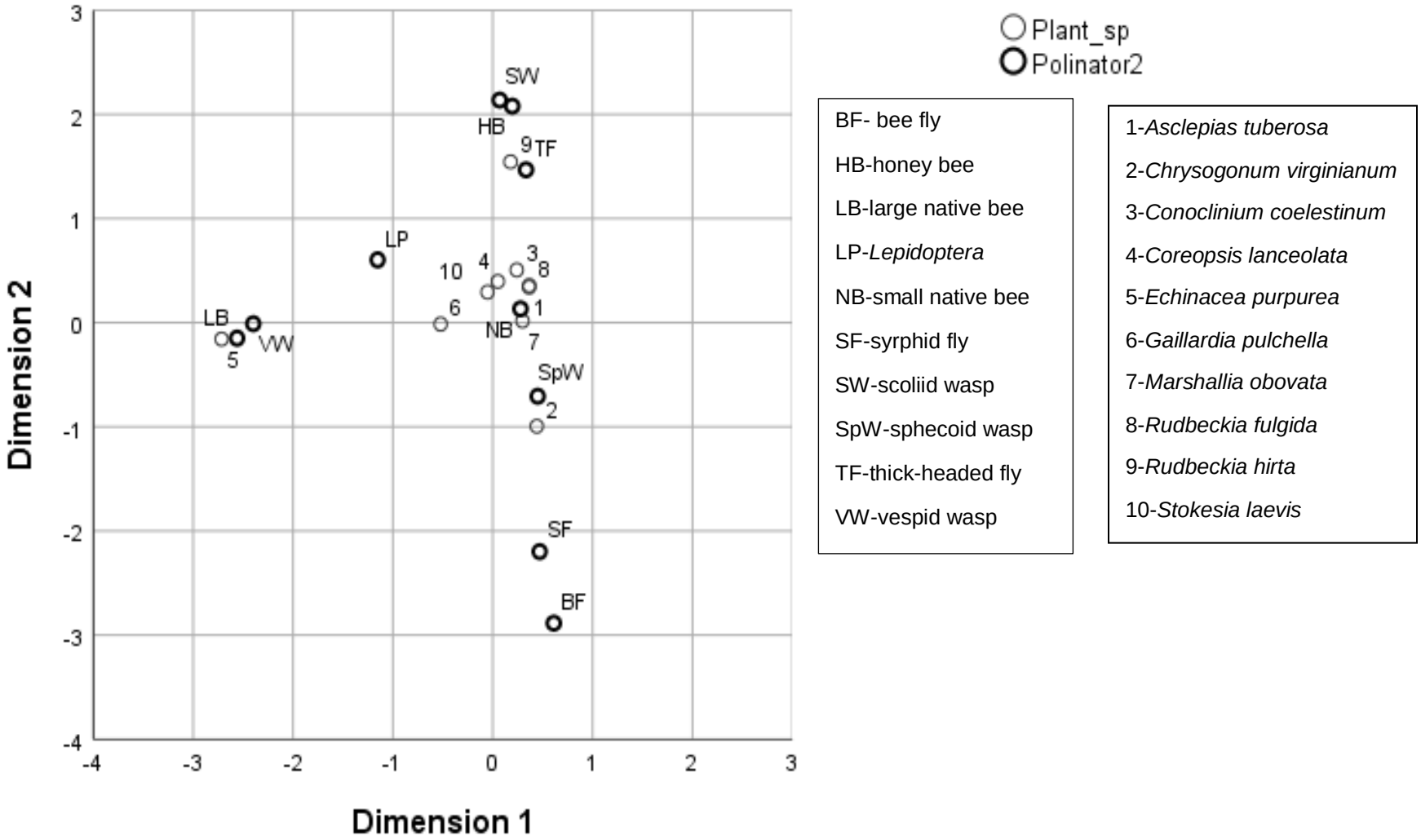


Fig. 11: Correspondence analysis of ten native plant species and insect visitors at the ECU Belk Bayer Feed-A-Bee™ site in 2018.



BF- bee fly

HB-honey bee

LB-large native bee

LP-*Lepidoptera*

NB-small native bee

SF-syrphid fly

SW-scoliid wasp

SpW-sphecoid wasp

TF-thick-headed fly

VW-vespid wasp

1-*Asclepias tuberosa*

2-*Chrysogonum virginianum*

3-*Conoclinium coelestinum*

4-*Coreopsis lanceolata*

5-*Echinacea purpurea*

6-*Gaillardia pulchella*

7-*Marshallia obovata*

8-*Rudbeckia fulgida*

9-*Rudbeckia hirta*

10-*Stokesia laevis*

Fig. 12: Correspondence analysis of ten native plant species and pollinator morpho-groups observed visiting at the ECU Belk Bayer Feed-A-Bee™ site in 2018.

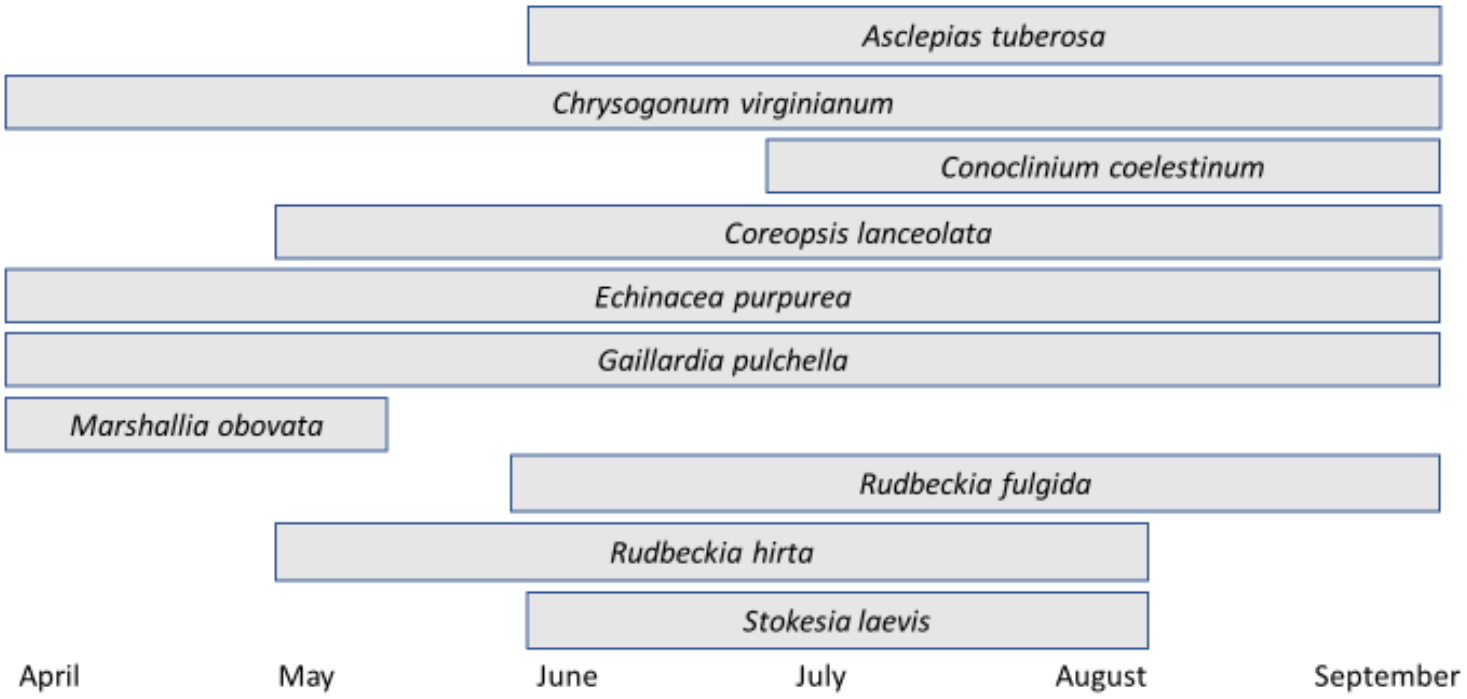


Fig. 13: Observed flowering period for each of the ten observed native plants in the ECU Belk Bayer Feed-A-Bee™ site in 2018.

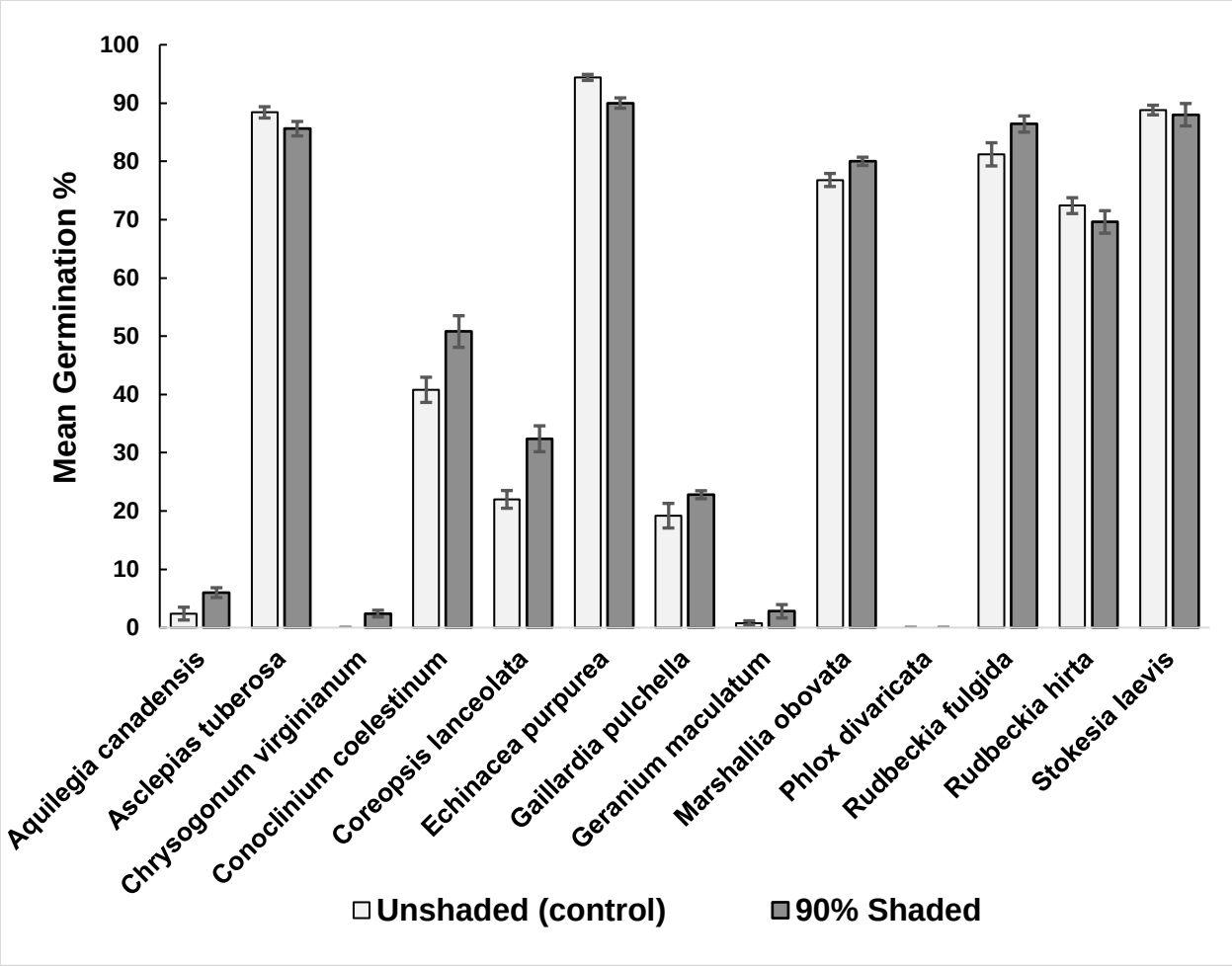


Fig. 14: Mean ± SE percent germination of 13 NC native plant species under 90% shaded and unshaded (control) conditions in the greenhouse. There was no significant difference in the mean germination between shade and control treatments using t-test to compare mean number of germinants (50 seeds per pot) between shaded and unshaded controls.

Fig. 15: Six simulated photovoltaic (PV) panel arrays in Pitt Co., NC. The panel dimensions are 1.2 m wide x 2.4 m long; 30 cm above ground surface. Eight 28 cm diameter landscaped rings in shaded and unshaded treatments contain seeds of randomly arranged native plant species, used in the Fall 2018-Spring 2019 field germination experiment.

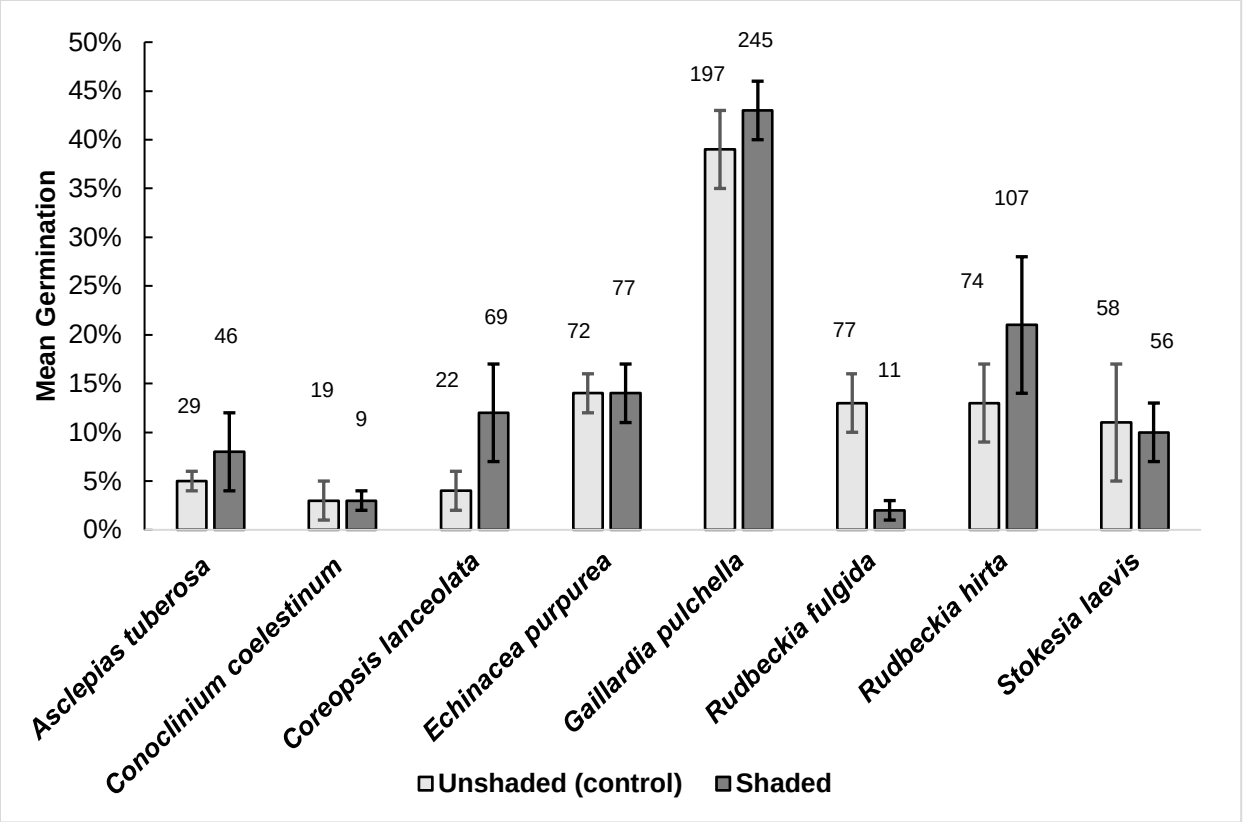


Fig. 16: Mean ± SE percent germination of eight NC native plant species in a field setting under shaded and unshaded (control) conditions. Numbers above each of the columns are total number of germinants for each treatment. Given small sample sizes, means were not compared statistically.

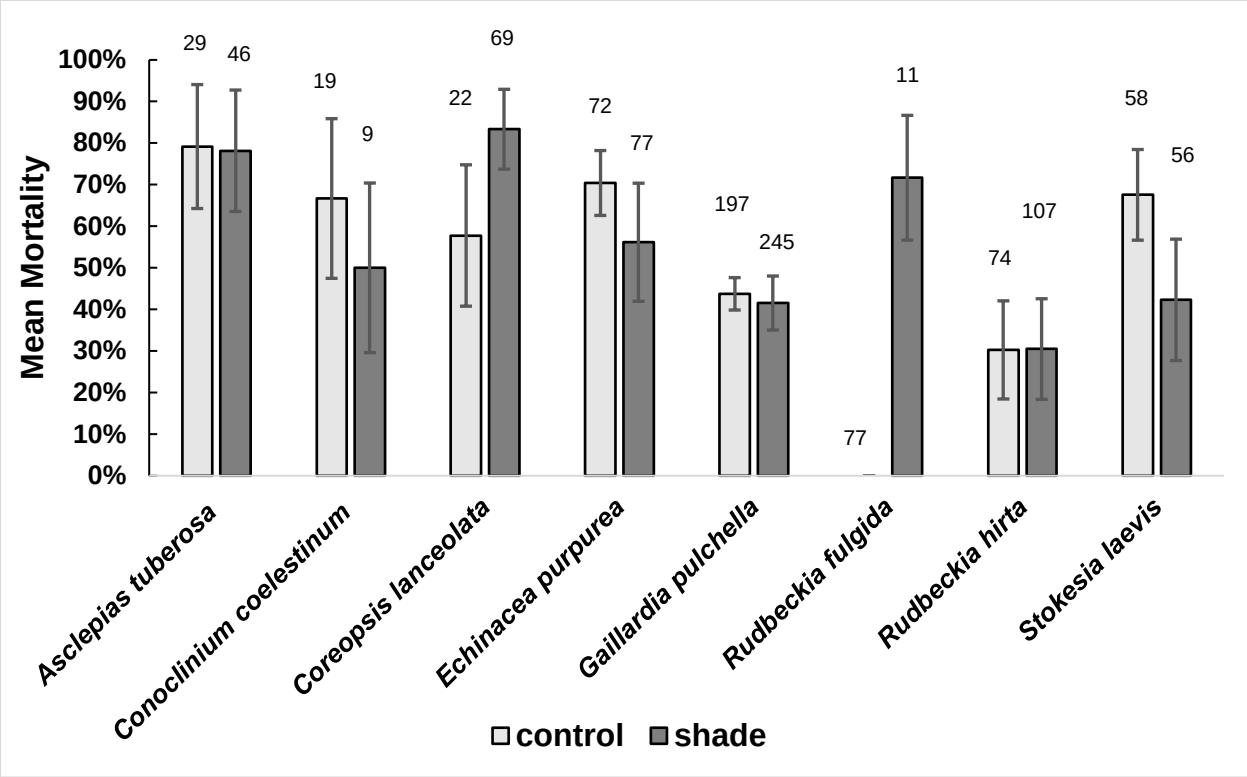


Fig. 17: Mean ± SE percent mortality of eight NC native plant species in a field setting under shaded and unshaded (control) conditions. Numbers above each of the columns are total number of germinants for each treatment. Given small sample sizes, means were not compared statistically.

SUPPLEMENTARY MATERIAL APPENDIX A

A.1: Additional resources used in selecting native plant species for pollinator habitat.

American Meadows Inc. 2018. Southeast pollinator wildflower seed mix. https://www.americanmeadows.com/wildflower-seeds/wildflower-mix/southeast-pollinator-wildflower-seed-mix (accessed 4 January 2018).

Maha, G. 2014. SEEDS Pollinator Plant List. http://www.seedsnc.org/wp-content/uploads/2014/12/Pollinator-Plants-List.pdf (accessed 3 January 2018).

North Carolina Audubon. 2017. North Carolina executive mansion bird and pollinator garden plant list. http://nc.audubon.org/sites/g/files/amh416/f/executive_mansion_garden_plant_list_with_partner_nurseries.pdf (accessed 1 January 2018).

NC Native Plant Society. 2017. Garden with natives. http://www.ncwildflower.org/native_plants/recommendations (accessed 3 January 2018).

North Carolina State Extension. 2017. Landscaping for wildlife with native plants: urban wildlife. https://content.ces.ncsu.edu/landscaping-for-wildlife-with-native-plants (accessed 3 January 2017).

North Carolina Wildlife Federation (NCWF). 2017. Native pollinator plants: recommended native plants for the butterfly highway. http://ncwf.org/programs/garden-for-wildlife/butterfly-highway/native-pollinator-plants/ (accessed 3 January 2018).

Roos, D. 2012. Top 25 Native Pollinator Plants for North Carolina. North Carolina Cooperative Extension. https://growingsmallfarms.ces.ncsu.edu/wp-content/uploads/2012/08/Top-25-Plants-and-Suppliers-2.pdf?fwd=no (accessed 3 January 2018).

SUPPLEMENTARY MATERIAL APPENDIX B:

Native plant sources surveyed for native shade tolerant perennials. Nurseries with bolded font are the sources of the plants used in pollinator beds and seeds used in germination experiments.

Nursery	Website Address
American Meadows	http://www.americanmeadows.com/
Cardno Native Plant Nursery	http://www.cardnonativeplantnursery.com/
Carolina Native Nursery	http://www.carolinanativenursery.com/
Carolina Seasons	http://www.carolinaseasons.com/
Cure Nursery	http://www.curenursery.com/
Ernst Seed	http://www.ernstseed.com/
Gardens in the Wood of Grassy Creek	http://www.gardensinthewood.com/
Lumber River Native Plants	http://www.ncnativeplants.com/
Mail Order Natives	http://www.mailordernatives.com/
Mellow Marsh Farms	http://www.mellowmarshfarm.com/
Niche Gardens	http://nichegardens.com/
Plant and See Nursery	http://www.plantandseenursery.com/
Prairie Moon Nursery	http://prairiemoon.com/
Prairie Nursery	http://www.prairienursery.com/
Wetland Plants Inc.	http://www.coastalplainnursery.com/
Worthington Farms	http://www.worthingtonfarms.com/
The Xerces Society	http://www.xerces.org/